
LISA Science Requirements Document

LISA International Science Team

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1 INTRODUCTION

1.1 Purpose

The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational-wave detector. LISA will use laser interferometry to detect gravitational waves from astrophysical sources throughout the Universe at frequencies between about 0.03 mHz and 1 Hz.

This Science Requirements Document (ScRD) defines the performance of the LISA mission required by the science objectives. The science objectives are established by the LISA International Science Team (LIST), the joint ESA-NASA science definition team. The LISA ScRD is the primary description by the science community of the science that the mission should accomplish. It is submitted by the LIST to the Project to guide the project formulation studies, and to the science program management of both agencies to either be the top level science statement in the case of ESA, or to support the writing of level 1 requirements in the case of NASA.

1.2 Scope

The Science Requirements Document states the top-level performance requirements necessary to fulfill the mission's science objectives. This document links science objectives to observation requirements to baseline performance requirements. The science objectives are broad science goals that LISA is expected to achieve. The objectives are broken down into science investigations that underlie the goals. The observation requirements are chosen to support the science investigations and specify the observations that the mission must make. The baseline requirements specify an instrument performance that will satisfy the observation requirements, and those baseline requirements define the capabilities that the combined flight and ground systems must have to fulfill the scientific investigations. However, the Level 1 Requirements Document establishes the ultimate scientific and technical requirements that govern the Project.

This document also contains minimum requirements. In the view of the LIST, if the mission concept is unable to achieve this minimum level of performance, the Project should be subjected to a review.

The LISA International Science Team, its working groups and supporting teams from the research community have prepared this Science Requirements Document. The LIST is the international science definition team for the LISA mission. It was originally established in 2001, and succeeded predecessor bodies in both Europe and the U.S., dating as far back as 1993.

This version of the ScRD supercedes all previous versions.

1.3 Configuration Management

This document is produced by the LIST, and that body initiates changes to it. The LISA Project receives the document from the LIST, evaluates the design consequences and notifies the LIST of its findings so that the science team can consider further changes to optimize the mission's science return within the larger context of space science. After several such iterations, the Project will accept the document as the baseline to which the Project works. Each version of the document delivered by the LIST shall be controlled using the procedures of the LISA Project Configuration Management Procedure. Those versions formally accepted by the Project shall be indicated by the appropriate signatures of the project managers.

1.4 Applicable Documents

The current understanding of the science behind the Science Requirements Document is described in *LISA: Probing the Universe with Gravitational Waves* (LISA Mission Science Office 2007). Note that, over the history of the LISA concept, there have been major advances in the understanding of the astrophysics and the fundamental physics underlying LISA science.

The scientific goals and objectives and the associated measurement performance of LISA have been developed over a long period. Important prior documents are:

Bender et al., *Laser Interferometer Space Antenna for the Detection and Observation of Gravitational Waves: Pre-Phase A Report*, 2nd ed., November 1998.

LISA - A Cornerstone Mission for the observation of gravitational waves: System and Technology Study Report, ESA-SCI(3000)11, corrected version 1.04 (13 Sep. 2000), 342 pp (2000).

The scientific goals and objectives of the LISA mission are consistent with the following U.S. and ESA reviews, agency roadmaps and strategic plans.

Gravitational Physics: Exploring the Structure of Space and Time, Committee on Gravitational Physics, Board on Physics and Astronomy, National Research Council, (National Academy Press), 126 pp (1999).

Astronomy and Astrophysics in the New Millennium, Astronomy and Astrophysics Survey Committee, Space Studies Board, National Research Council, (National Academy Press), 276 pp (2001).

Connecting Quarks with the Cosmos : Eleven Science Questions for the New Century, Committee on the Physics of the Universe, Board on Physics and Astronomy, National Research Council, (National Academy Press), 222 pp (2003).

Letter report of the Committee to Assess Progress Toward the Decadal Vision in Astronomy and Astrophysics, Committee for Astronomy and Astrophysics, National research Council, (11 Feb. '05 letter from M. Urry to A.V. Diaz and M. S. Turner) 24 pp (2005).

Annual Report , Astronomy and Astrophysics Advisory Committee March 16, 2003 – March 15, 2004
(http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2004_report.pdf).

Annual Report , Astronomy and Astrophysics Advisory Committee March 16, 2004 – March 15, 2005
(http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2005_report.pdf)

Annual Report, Astronomy and Astrophysics Advisory Committee March 16, 2005 – March 15, 2006
(http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2006_report.pdf)

Beyond Einstein: from the Big Bang to Black Holes, Structure and Evolution of the Universe Roadmap Team: Beyond Einstein Roadmap (NASA) 112 pp (2003).

Cosmic Journeys: To the Edge of Gravity, Space and Time, Structure and Evolution of the Universe Roadmap: 2003-2023, Structure and Evolution of the Universe Subcommittee of the Space Science Advisory Committee (NASA) 73 pp (1999).

NASA Science Plan, Draft 6.0 (NASA), 165 pp (20 Nov. 2006).

Horizon 2000, (ESA, SP-1070), December 1984.

Horizons 2000+, Bonnet, Roger-Maurice, (ESA, SP- 1180, Revision 1; ISBN 92-9092-157-9), August 1995.

Cosmic Vision: Space Science for Europe 2015-2025, (ESA, BR-247), 111 pp, October 2005.

1.5 Definitions

The following definitions apply throughout this document.

1.5.1 Requirements

Observation requirements are derived from LISA's science objectives and the specific investigations needed to fulfill those objectives. The observation requirements are given in terms of observable quantities, such as those defining the source to be observed (e.g., masses, redshift, etc.), the required precision of a parameter estimate or the minimum number of objects to be observed. An observation requirement must be sufficiently defined so that a forward calculation of the instrument performance can be made to confirm that it is achievable.

Baseline requirement is a specification of a system parameter or capability with which system design must comply, and be verified (e.g. by analysis, test, demonstration)

Minimum requirement - minimum performance floor acceptable. Descope, if necessary must meet these levels (i.e. these can turn into baselines of a descoped mission). Failure to meet these would trigger a Project review.

Goals - performance parameters that would significantly enhance scientific return. These do not drive mission design, and are not required to be verified. Project just attempts a mission design that does not preclude achieving the goals, and tracks them, so that if resources allow the better performance can be achieved.

1.5.2 Conventions

Sensitivity - LISA sensitivity requirements are stated in terms of the strain amplitude spectral density, $\sqrt{S_h(f)}$, defined as the square root of the single-sided, sky-averaged, polarization-averaged amplitude spectral density of gravitational wave strain measured in the “Michelson” X observable of TDI (i.e. using two arms of the LISA constellation). For a discussion of TDI see e.g. Estabrook et al. (2002). The sensitivity has units of $\text{Hz}^{-1/2}$.

Signal-to-Noise Ratio (SNR) – With this convention, for example, the sky-averaged SNR of a sweeping source with characteristic amplitude h_c is given by :

$$SNR^2 = \int \frac{h_c^2(f)}{f S_h(f)} d(\ln f)$$

All SNRs quoted are for isolated sources (but including the conventional Gaussian approximation to galactic white dwarf noise), optimal signal processing, Gaussian instrumental noise, and duty cycle $\eta=1$.

T_{obs} – Time during which observations are actually taken.

Links – One-way, measured distances.

2 MISSION DESCRIPTION

The LISA mission concept has been under development for two decades (cf Faller et al. 1985), and has been intensively studied since being proposed for ESA's M3 opportunity in May 1993. The current concept has been quite stable since 1997, with most of the advance in progressively detailed design and analysis. The basic elements have remained unchanged. Those elements are: three spacecraft, three roughly equal measurement baselines, passive heliocentric orbits, "drag-free" spacecraft following free-falling proof masses, interferometric ranging, solid-state lasers, and electro-spray thrusters.

By contrast, the science that LISA can do has grown very considerably over the same time period. Massive black holes are now thought to be commonplace in galaxies with bulges. Those black holes and their host galaxies are thought to co-evolve. Massive black hole mergers resulting from galactic mergers are now thought to occur at much higher rates than when LISA was first proposed. Numerical relativists have successfully calculated the waveforms from merging black holes, providing a test of extreme dynamical gravity. Cosmology has become an experimental science. Dark energy has been discovered. The serendipitous consequence of these advances is that while the LISA concept has matured, the science reach of that concept has increased substantially with essentially the same performance. The science requirements in this document have benefited from a sustained review of mission performance and science opportunities.

2.1 LISA Science

The document *LISA: Probing the Universe with Gravitational Waves* (LISA Mission Science Office 2007) describes the science that LISA is expected to perform. There is also a primer on gravitational waves, their detection and their astrophysical sources.

Appendix 1 of that document lists the LISA science objectives and science investigations. Those objectives and investigations are repeated at the beginning of Chapter 4 of this document.

This *LISA Science Requirements Document* lays out the performance requirements necessary to support this science. The requirements in Section 4 are organized around these science objectives for the LISA mission. Some of the related objectives are grouped together in the subsections.

To carry out the science investigations in Chapter 4, LISA will measure the time-varying strains in space-time caused by gravitational waves in the frequency band 0.03 millihertz (mHz) to 1 Hz. It does this through very accurate laser metrology between pairs of spacecraft in a constellation of 3 spacecraft. The measurement methodology is that of laser spacecraft Doppler tracking. A strain amplitude spectral sensitivity (square root of the power spectral density) on the order of $10^{-20} / \sqrt{\text{Hz}}$ is necessary to

detect expected astrophysical signals, extract astrophysical information from them, and carry out tests of fundamental physics with those signals. Based on conservative estimates of source event rates, LISA requires this measurement capability for 5 years. {N.B. It is the custom in gravitational wave detection to use amplitude spectral density to characterize time-varying strain and noise processes that determine instrument sensitivity, because gravitational wave interferometers measure amplitude, rather than power, as many electromagnetic photon detectors do.}

The required instrument performance takes the form of a model, which accounts for both the instrumental noise and response function. Because the Observation Requirements cannot simply be inverted for the required instrument performance, this sensitivity model is chosen in the ScRD so as to satisfy the Observation Requirements by a forward calculation of detection. The ScRD noise model is described in Chapter 3 of the ScRD

To carry out the investigations in Section 4, LISA will measure signals from the following source types:

- Massive black hole binaries – Mergers of binaries involving two black holes with mass M in the range $10^4 M_{\odot} < M < 10^7 M_{\odot}$. Normally, LISA will detect the late inspiral when sufficient gravitational radiation is being produced (\sim months to years), and in some instances the merger event and subsequent ringdown of the event horizon. Depending on the source parameters, LISA can detect signals from events as far away as $z \sim 30$, although the luminosity distance may not be precisely determined at these very high redshifts. Current estimates suggest that LISA should see tens to hundreds of massive black hole mergers per year.
- Intermediate-mass black holes – Mergers of binaries involving at least one black hole with mass $10^2 M_{\odot} < M < 10^4 M_{\odot}$. LISA could detect these events out to $z \sim 20$, and could get accurate parameter estimation out to $z \sim 10$. Rate estimates are very uncertain, but could be high.
- Extreme-mass ratio inspirals – Stellar-mass compact objects (i.e., black holes, neutron stars and white dwarfs) with $M \sim 10 M_{\odot}$ scattered into long-lived, highly elliptical capture orbits around massive black holes in galactic nuclei. LISA can detect these events and get valuable parameter estimates out to $z \sim 1$. The best estimate of the detection rate is 20-40/yr, but could be substantially higher or lower.
- Close binaries of stellar-mass compact objects – Close binary systems of stellar-mass black holes, neutron stars and white dwarfs in the Milky Way with orbital periods between 100 and 10,000 seconds will be very numerous so LISA will easily detect several thousand of the brightest sources. The remainder will constitute a diffuse foreground signal between 0.2 and 2 mHz. Extragalactic systems of the same type will contribute a weak diffuse foreground signal only between 2 and 3 mHz.

LISA might also detect signals from cosmological backgrounds, bursts from cosmic string cusps, and unforeseen sources.

This science and these sources are qualitatively different from the science and sources of ground-based gravitational wave detectors. A space-based instrument can detect gravitational radiation with much lower frequencies, and the Universe happens to offer the richest array of sources at those lower frequencies.

2.2 Mission Concept

The concept described in this section has notional values of some top-level design parameters. The particular values used here are not a prescription for those parameters, but rather are suggestive of the approximate order of magnitude intrinsic to the underlying concept.

LISA is a gravitational wave detector based on an interferometer. It measures time-varying strains in space-time by interferometrically monitoring changes in baselines millions of kilometers long. The mission concept requires two basic functions: undisturbed masses to act as the endpoints of the baselines and a measurement system to monitor changes in the lengths of the baselines. The disturbance of the masses must be sufficiently small that the resulting motions are less than the apparent length changes associated with gravitational waves to be detected. Likewise, the measurement system must be able to detect those apparent length changes.

The baselines are defined by three spacecraft orbiting the Sun (see Figure 2-1). A key feature of the LISA concept is that there exist orbits that do not require station-keeping to maintain a near-equilateral triangular formation a fixed distance from the Earth for the duration of the mission. The spacecraft at the corners house interferometry equipment for measuring changes in the baselines and ‘proof masses’ which define their endpoints.

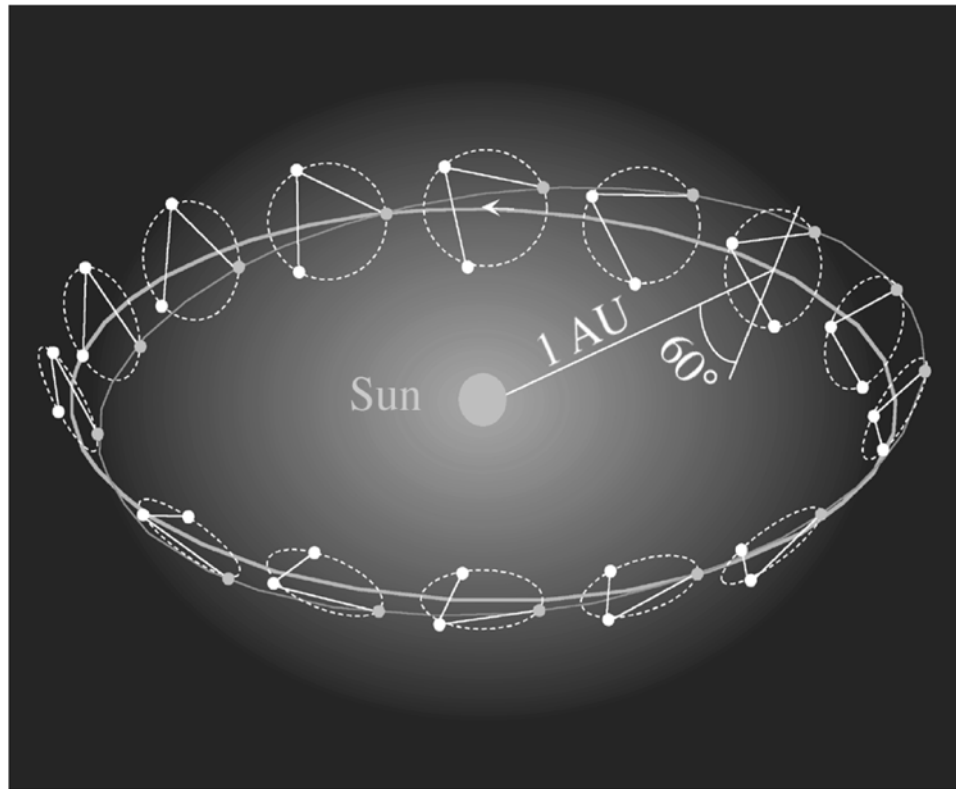


Figure 2-1. LISA Orbits. The spacecraft are represented by 3 dots in the snapshots of the formation's annual motion around the Sun. The thick line is the ecliptic. The orbit of one spacecraft is traced by the inclined circle running through the same dot in each snapshot.

The proof masses are protected from disturbances by careful design and “drag-free” operation. In drag-free operation, the mass is free-falling, but a housing around the proof mass senses the relative position of proof mass and spacecraft, and a control system commands the spacecraft’s thrusters to follow the free-falling mass. Drag-free operation keeps force gradients arising in the spacecraft from applying time-varying disturbances to the proof masses.

The distance measuring system is essentially a continuous interferometric laser ranging scheme. Lasers at each end of each arm operate in a “transponder” mode. A beam is sent out from one spacecraft to a distant one. The laser in the distant spacecraft is phase-locked to the incoming beam and returns a high power phase replica. When that beam returns to the original spacecraft, it is beat against the local laser. Variants of this basic scheme are repeated for all long baselines, and the lasers illuminating different baselines are also compared. Optical path difference changes, laser frequency noise, and clock noise are determined.

Achievable levels of disturbance on proof masses and achievable sensitivities of laser ranging system make it possible to obtain a useful measurement bandwidth in the frequency regime of 10^{-5} to 1 Hz. This band has many types and large numbers of gravitational wave sources, some likely very strong.

The three arms can simultaneously measure both polarizations of quadrupolar waves. The source direction is decoded from amplitude, frequency, and phase modulation caused by annual orbital motion of the antenna and its sensitivity pattern across the sky.

3 SUMMARY OF SCIENCE REQUIREMENTS

In this LISA Science Requirements Document, a model of instrument sensitivity is the main description of the requirements levied by the science against the mission design. In Chapter 4, the science objectives and science investigations are rendered into Observation Requirements. A selected Instrument Sensitivity Model (ISM) is evaluated against the Observation Requirements to show that a mission design whose performance equals or exceeds the model sensitivity can fulfill the science objectives. The ISM is a relatively generic model of the space-based gravitational wave detector concept described in §2.2 based on three parameters: an acceleration noise, a displacement noise, and the arm length of the interferometer.

The ISM is given in §3.1. The model and other baseline requirements are summarized in §3.2. The minimum requirements developed in Chapter 5 are summarized in §3.3. Additional performance goals are summarized in §3.4. The process for validating the ISM is described in §3.5.

3.1 Instrument Sensitivity Model

The noise model for the LISA instrument calculates the strain noise amplitude spectral density $\sqrt{S_h(f)} = \Delta L(f)/2L$ as the product of several terms:

$$\sqrt{S_h(f)} = (\sqrt{5}) \times \left(\frac{2}{\sqrt{3}}\right) \times T(f) \times \frac{\sqrt{S_{\delta x_IMS}(f) + S_{\delta x_DRS}(f)}}{L},$$

where the measurement band is defined from 0.03 to 100 mHz. The first term, $\sqrt{5}$, represents the results of averaging the antenna response over the full sky. The second term, $1/\sin(60^\circ) = 2/\sqrt{3}$, accounts for the projection effect of the equilateral triangular geometry of the detector onto the response of the optimum detector, which is an L-shaped Michelson. The transfer function $T(f)$, described in §3.1.2, represents the conversion of single link position uncertainty into the detector strain response, including the finite light travel time of the arm and the Time Delay Interferometry (TDI) Michelson X variable response. The variables $S_{\delta x_IMS}(f)$, $S_{\delta x_DRS}(f)$ and L are the power spectral density of the displacement noise from the measuring system, the power spectral density of the displacement noise from spurious accelerations on the proof masses and the arm length of the interferometer, respectively.

The LISA sensitivity model is plotted in Figure 3-1.

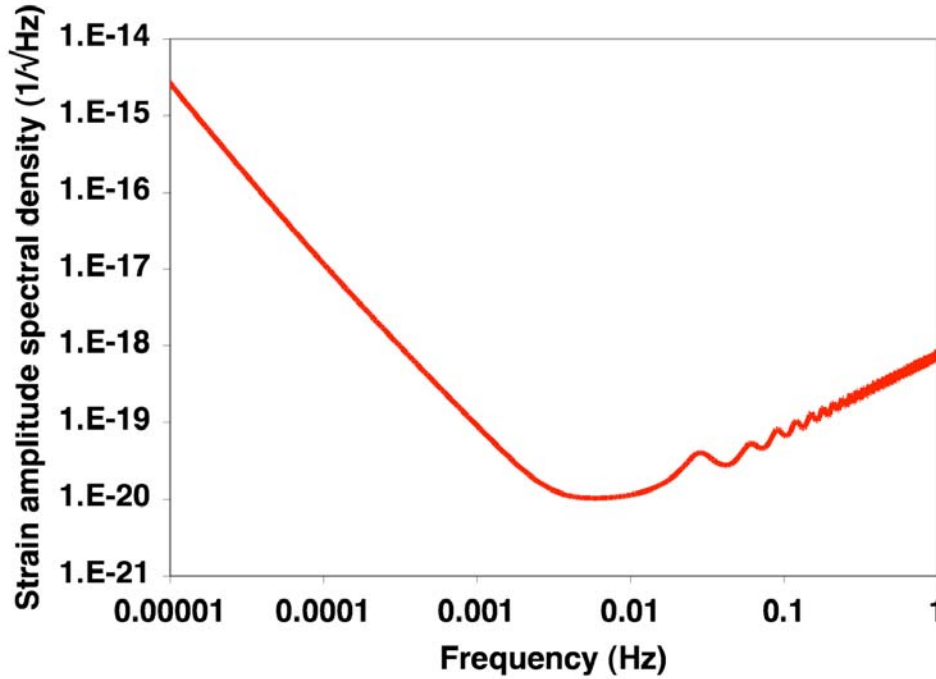


Figure 3-1: LISA Sensitivity Curve. The strain amplitude spectral density of the Instrument Sensitivity Model is plotted. The measurement bandwidth extends from 0.03 mHz to 100 mHz.

3.1.1 Instrument Noise Model

The single link equivalent position uncertainty is expressed as an amplitude spectral density whose power spectral density is the sum of two terms – the displacement noise of the Interferometry Measurement System (IMS), and the acceleration noise of the Disturbance Reduction System (DRS), which is responsible for minimizing the residual acceleration of the proof masses:

$$\sqrt{S_{\delta x_single_link}(f)} = \sqrt{S_{\delta x_IMS}(f) + S_{\delta x_DRS}(f)}$$

The displacement noise amplitude spectral density $\sqrt{S_{\delta x_IMS}(f)}$ for the uncertainty in the interferometry measurement system is given by:

$$\sqrt{S_{\delta x_IMS}(f)} = \Delta X_0 \times 10^{-12} \frac{m}{\sqrt{Hz}} \times \sqrt{1 + \left(\frac{f_0}{f}\right)^4}; 3 \times 10^{-5} \leq f \leq 10^{-1} Hz,$$

with $\Delta X_0=18$, $f_0=.002$ Hz.

The displacement noise amplitude spectral density $\sqrt{S_{\delta x_DRS}}(f)$ for the uncertainty in the DRS is calculated from an amplitude spectral density for the residual acceleration on the proof masses

$$\sqrt{S_{\delta x_DRS}}(f) = \Delta A_0 \times 10^{-16} \frac{m}{s^2 \sqrt{Hz}} \sqrt{1 + \left(\frac{f}{f_H}\right)^4} \sqrt{1 + \left(\frac{f_L}{f}\right)^2}; 3 \times 10^{-5} Hz \leq f \leq 10^{-1} Hz,$$

with $\Delta A_0 = 30$, $f_L = .0001 Hz$, $f_H = .008 Hz$.

The equivalent displacement noise amplitude spectral density is then given by:

$$\sqrt{S_{\delta x_DRS}}(f) = 2 \frac{\sqrt{S_{\delta a_DRS}}(f)}{(2\pi f)^2}; 3 \times 10^{-5} Hz \leq f < 10^{-1} Hz$$

where the factor of two accounts for the presence of four proof masses in the measurement of the difference in length of two arms, and the $1/(2\pi f)^2$ is the conversion from acceleration to position in Fourier space.

3.1.2 Instrument Transfer Function

The instrument transfer function in §3.1 describes the instrument's response to gravitational waves of different frequencies. As LISA's response to gravitational waves depends in a complex way on the position of the source in the sky, the polarization of the wave and its frequency, the sensitivity is conventionally averaged over all possible sky locations and polarizations.

The instrument transfer function, as discussed in e.g. Schilling (1997) or Larson et al (2000), is often written containing all the effects of the averaging, but it is clear that any transfer function can always be normalized to be 1 at a given frequency and the remaining numerical factor be absorbed in the instrument sensitivity.

The choice made in this document is to normalize the transfer function at low frequencies, where it shows a flat frequency dependence, i.e. LISA's response does not depend on the frequency of the gravitational wave if this frequency is low enough.

For high frequencies ($f > c/(2L)$, where L is the arm length), the response of LISA decreases. When the arm length L is an integer multiple of half of the effective wavelength of the gravitational wave, the effect of the wave on that arm vanishes. So only the difference of the arm length to the maximum number of half effective wavelengths, the effective arm length, is affected by the gravitational wave. The higher the frequency of the gravitational wave, and consequently the shorter its wavelength, the smaller the effective arm length becomes and the smaller the absolute change of the effective arm length becomes. So, in general, a decrease proportional to $1/f$ should be expected, with a transition between the constant part at low frequencies and the high frequency decline at $f_0 = c/(2L)$.

Furthermore, at frequencies where the wavelength of the gravitational wave is an exact integer multiple of the arm length, the effect in this arm vanishes. In an interferometer

with two identical arms, the overall effect vanishes. This leads to a loss of sensitivity for a given frequency. As gravitational waves from sources at different sky positions but same frequency have different angles of incidence on LISA, their effective wavelength, i.e. the wavelength projected on the arm, differs. This causes the transfer function to never go to infinity but to just increase by about a factor of 2 at these frequencies.

Unfortunately, there is no analytic model of the instrument transfer function that accurately displays all its features. A numerical representation of the transfer function is plotted in Figure 3-2. If the more complex structure at higher frequencies is not of interest, the following approximation can be used

$$T(f) = \sqrt{1 + \left(\frac{f}{af_0}\right)^2} \quad \text{where } f_0 = c/(2L) \text{ and } a = 0.41.$$

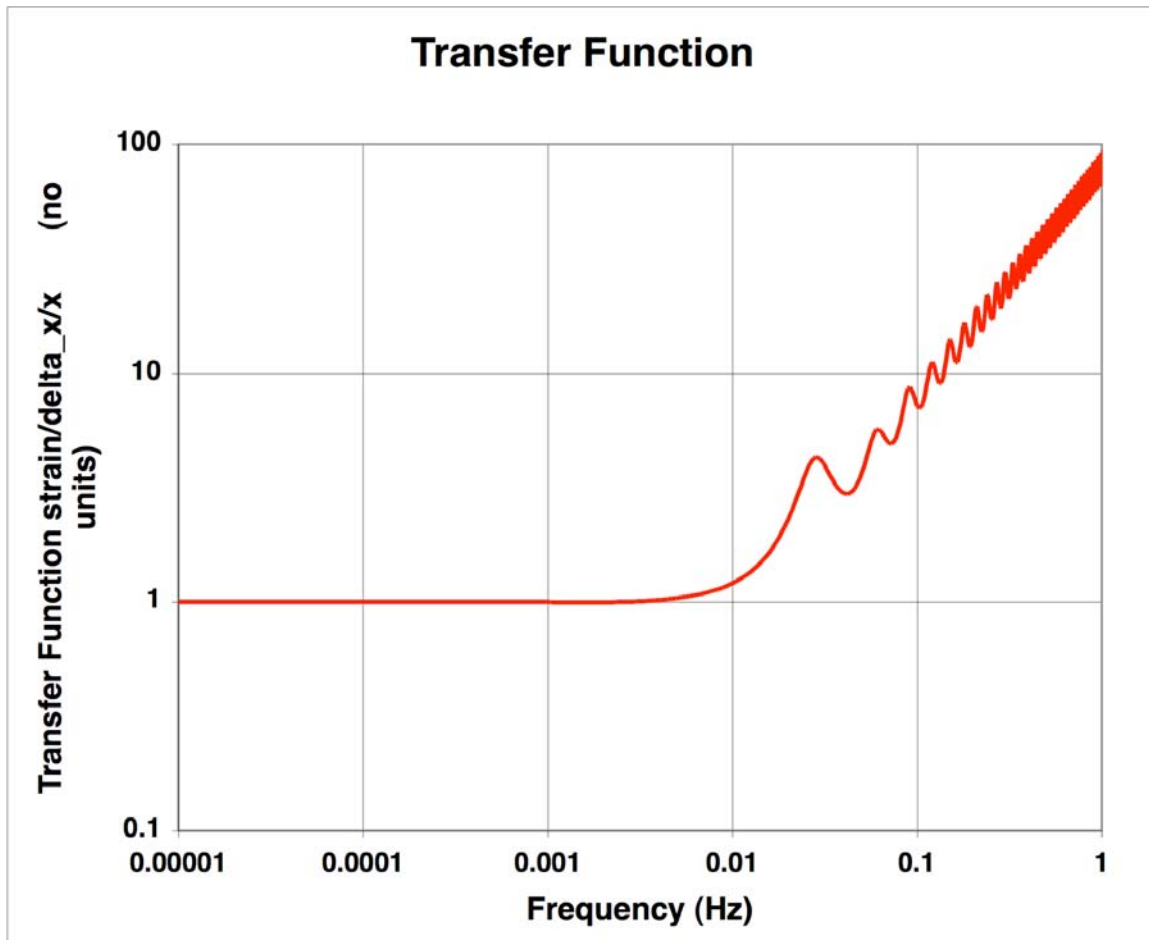


Figure 3-2: Instrument transfer function from displacement uncertainty to strain.

3.2 Baseline Requirements

The baseline requirements consist of the ISM that satisfies all of the Observation Requirements in Chapter 4 and any other miscellaneous requirements on the performance of the mission stated in the Observation Requirements.

LISA shall have a sensitivity better than or equal to the Instrument Sensitivity Model given in §3.1.

LISA shall have a useful science observing time of 5 years.

LISA shall be designed for 3 spacecraft with 6 working links (two interferometers) and the design shall ensure 2 operating arms for the full mission duration.

LISA shall be capable of identifying and announcing the time of a massive black hole merger at least two weeks prior to the merger.

LISA shall be capable of collecting science data without scheduled interruption for 4 days about the time of a massive black hole merger.

LISA shall have the capability of distinguishing between instrumental and environmental noise and gravitational wave signals above the sensitivity threshold.

3.3 Minimum Requirements

The minimum requirements consist of an ISM which satisfies all of the Observation Requirements in Chapter 5 and any other miscellaneous requirements on the performance of the mission stated in those Observation Requirements.

LISA shall have a sensitivity better than or equal to an instrument sensitivity five times higher than the baseline Instrument Sensitivity Model given in §3.1 from 0.1 to 10 mHz.

LISA shall have a useful science observing time of 2 years.

LISA shall have at least four measured links (one interferometer) for the duration of scientific observations.

LISA shall be capable of collecting science data without scheduled interruption for 4 days about the time of a massive black hole merger.

LISA shall have science observation duty cycle (η) greater than 0.75

3.4 Performance Goals

This section summarizes the goals requested by the science objectives and investigations in Chapter 4.

LISA shall have as a goal a sensitivity better than or equal to the Instrument Sensitivity Model given in §3.1, extended to 1 Hz.

LISA shall have as a goal 6 working links (two interferometers) for the full mission duration.

LISA shall have as a goal an extended mission duration of 8.5 years.

3.5 Validating the Sensitivity Model

The Instrument Sensitivity Model is the core of the baseline requirements derived from the mission science. Since it is very difficult, if not impossible, to directly invert the Observation Requirements in Chapter 4 for the required instrument performance, it is necessary to do the forward calculation of the instrument performance with a instrument model to verify that the Observation Requirements can be met. The process of verifying that the ISM will in fact enable the required observations is generically summarized in this section. This section is not intended to provide all technical details of the calculation, but rather give the reader a sense of the undertaking.

An extensive literature on the gravitational wave emission, propagation and detection has developed over the last 30 years. The desired products are predictions of the signal-to-noise ratio in the detector and the uncertainty of source parameters extracted from the data. The number of extractable source parameters depends on the specific source, but may be as many as 17. Examples of parameters that might be extracted from a fully chirping binary are polar location (θ), azimuthal location (ϕ), inclination (i), polarization (ψ), initial orbital phase (ϕ_0), coalescence time (t_c), luminosity distance (D_L), chirp mass (M_c), and reduced mass (μ).

The process generically involves computing waveforms from the post-Newtonian equations of motion for the source of interest, taking account of the relative orientation and separation of the source and the detector, invoking the response of the detector in conjunction with both astrophysical and instrumental noise, and taking into account the estimation of the many parameters in the signal. The ISM enters this process as the instrument response and noise.

This general process differs from source to source with assumptions and methodologies appropriate to the source being considered. The best example of this process for binary black holes of the scenarios in many of the Observation Requirements in Chapter 4, see Lang and Hughes (2006). Their calculations underlie the tables shown in 4.1 and 4.2 and other science investigations, though with slightly different assumptions than described in their published paper. After each Observation Requirement discussed in Chapter 4, there is a review of the supporting calculation for that requirement.

The LISA Calculator (<http://www.physics.montana.edu/LISA/lisacalculator/>) is a particularly handy web-based tool for exploring the LISA performance in specific situations. Note that spin effects are not included, orbits are assumed to be circular, and mass ratios much greater than 100 may be suspect.

Many considerations enter into the details of this process. For example where binaries are concerned, the mass ratios, redshift, spin and precession effects, merger and ring-down signals, sky and polarization averaging, orbital eccentricity all affect choices in how the calculations are done. Background and burst detection pivots on still other considerations.

The following assumptions are made for the calculations supporting this document:

- Unless noted, only a single interferometer is used in the calculation. This is taken to add some redundancy against the risk of partial failure. Aside from conservative rate calculations, no other margin is carried in the science requirements.
- Both galactic and extragalactic binaries of compact stellar mass objects will be so numerous as to give confusion noise background at some level. Consequently, a complete noise model for the detection and parameter estimation process must include the astrophysical noise. Figure 3-3 illustrates a typical model (<http://www.srl.caltech.edu/~shane/sensitivity/>) of the galactic and extragalactic confusion noise backgrounds relative to the ISM from §3.1
- In all cases, the ISM is assumed to have no useful sensitivity below 0.03 mHz. In some cases, the ISM is assumed to have no useful sensitivity below 0.1 mHz.
- Except where specific sources known, these calculations usually use sky position and orientation averaging as a benchmark.

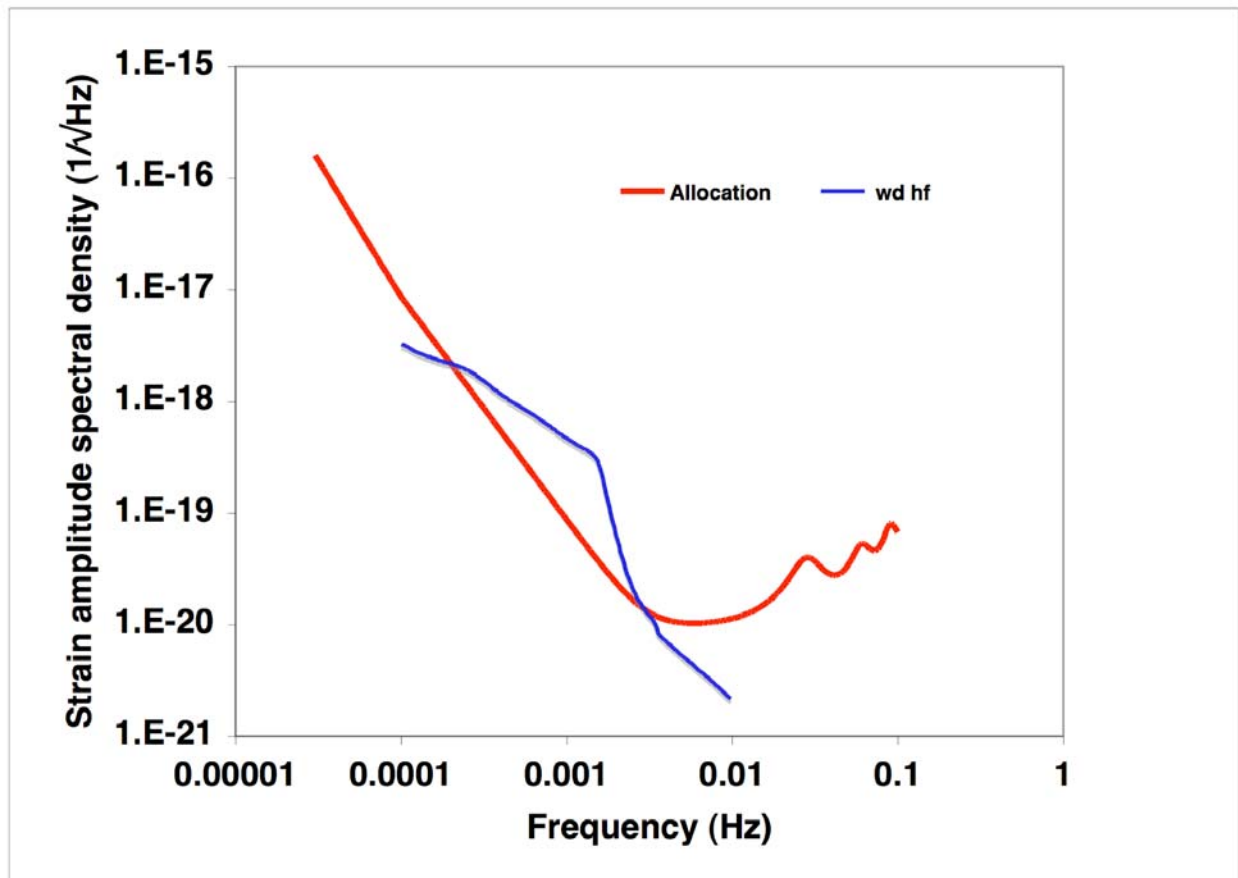


Figure 3-3. Standard instrument sensitivity model and binary confusion noise. The red curve is the product of the standard instrument noise model given above multiplied by the instrument transfer function shown in Fig. 3-2. The blue curve is the expected confusion noise threshold from galactic and extragalactic binaries.

4 REQUIREMENTS BY SCIENCE OBJECTIVES

This section connects the science objectives of LISA to the baseline performance requirements that drive the design of the mission. For each science objective, one or more science investigations are listed that will meet the objective. The investigations require that particular observations be made, and those are stated as Observation Requirements. A standard Instrument Sensitivity Model (ISM) was proposed in Chapter 3 that satisfies the Observation Requirements given below. That ISM and ancillary requirements summarized in §3.2 constitute the science requirements for the mission..

The science objectives are set out in Appendix 1 of *LISA: Probing the Universe with Gravitational Waves* (LISA Mission Science Office 2007). The science objectives and their investigations are summarized in Table 4-1.

Table 4-1. LISA science objectives and supporting science investigations.

Science Objectives	Science Investigations
Understand the formation and growth of massive black holes	Search for a population of seed black holes at early epochs
	Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs
Trace the growth and merger history of massive black holes and their host galaxies	Determine the relative importance of different black hole growth mechanisms as a function of redshift
	Determine the merger history of 1×10^4 to $3 \times 10^5 M_{\odot}$ black holes from the era of the earliest known quasars ($z \sim 6$)
	Determine the merger history of 3×10^5 to $1 \times 10^7 M_{\odot}$ black holes at later epochs ($z < 6$)
Explore stellar populations and dynamics in galactic nuclei	Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals
	Study intermediate-mass black holes from their capture signals
	Improve our understanding of stars and gas in the vicinity of galactic black holes using coordinated gravitational and electromagnetic observations

Survey compact stellar-mass binaries and study the morphology of the Galaxy	Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground
	Determine the spatial distribution of stellar mass binaries in the Milky Way and environs
	Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations
Confront General Relativity with observations	Detect gravitational waves directly and measure their properties precisely
	Test whether the central massive objects in galactic nuclei are the black holes of General Relativity
	Make precision tests of dynamical strong-field gravity
Probe new physics and cosmology with gravitational waves	Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured
	Measure the spectrum of, or set bounds on, cosmological backgrounds
Search for unforeseen sources of gravitational waves	

Each science investigation will lead to an observation of one or more of the anticipated source types. Consequently, there will be more than one observing requirement levied against a source type if more than one investigation relies on an observation of that source. This may lead to multiple observation requirements with similar values; such observations are more valuable for the multiple science investigations they support.

4.1 Understand the formation of massive black holes

The study of the formation, accretion history, and environmental impact of massive black holes (MBHs, $M > 10^4 M_{\odot}$) in the nuclei of galaxies provides invaluable insights into the quasar phenomenon, the evolution of active galactic nuclei, the relation between black holes and their host halos, the hierarchical growth of cosmic structures, and the astrophysics of some of the earliest formed sources of light.

Today, MBHs are ubiquitous in the nuclei of nearby galaxies (Ferrarese & Ford 2005; Tremaine et al. 2002; Greene, Barth, & Ho 2006). If MBHs were also common in the past (as implied by the notion that many distant galaxies harbor active nuclei for a short period of their life), and if their host galaxies experience multiple mergers during their lifetime, as dictated by standard cold dark matter (CDM) cosmologies, then MBH binaries will inevitably form in large numbers during cosmic history. MBH pairs that are able to coalesce in less than a Hubble time will be the loudest anticipated gravitational wave events in the Universe. LISA will detect mergers of comparable-mass MBH binaries (defined as binaries with total masses $M = M_1 + M_2 > 10^4 M_\odot$ and mass ratios $\mu/M > 0.01$, where μ is the “reduced mass”) throughout a wide range of redshifts.

The nomenclature describing black holes varies in the astrophysical literature. In this document, black holes with mass $< 100 M_\odot$ are referred to as “stellar-mass,” those with $10^2 M_\odot < M < 10^4 M_\odot$ are “intermediate-mass black holes” (IMBHs), and those with $10^4 M_\odot < M < 10^7 M_\odot$ are “massive black holes” (MBHs).

4.1.1 Search for a population of seed black holes at early epochs

The astrophysical processes that led to the formation of the first seed black holes and to their growth into the supermassive variety that powers bright quasars at $z=6$ are poorly understood. These seed black holes may have formed from the coalescence of stellar-mass black holes, the collapse of the first generation of massive stars (Population III), and/or the collapse of supermassive stars formed out of dense low-angular momentum gas. This investigation seeks to identify the earliest merger events of MBHs and, from these mergers events, shed light on the origin, mass distribution, numbers, and early growth mechanisms of the first seeds.

Standard CDM hierarchical cosmologies predict that the earliest MBHs formed at $z > 15$ in the centers of small dark matter halos (Abel, Bryan & Norman 2002; Bromm, Coppi & Larson 2002; Madau & Rees 2001; Volonteri & Rees 2005). Population III stars in the mass range $40\text{--}140 M_\odot$ and $> 260 M_\odot$ are predicted to collapse to black holes with masses exceeding half of the initial stellar mass (Heger & Woosley 2002). Some of these IMBHs may grow quickly through gas accretion and mergers to masses of $> 10^4 M_\odot$. This investigation seeks to identify the smallest BHs at the earliest times, consistent with adequate distance sensitivity to establish the epoch.

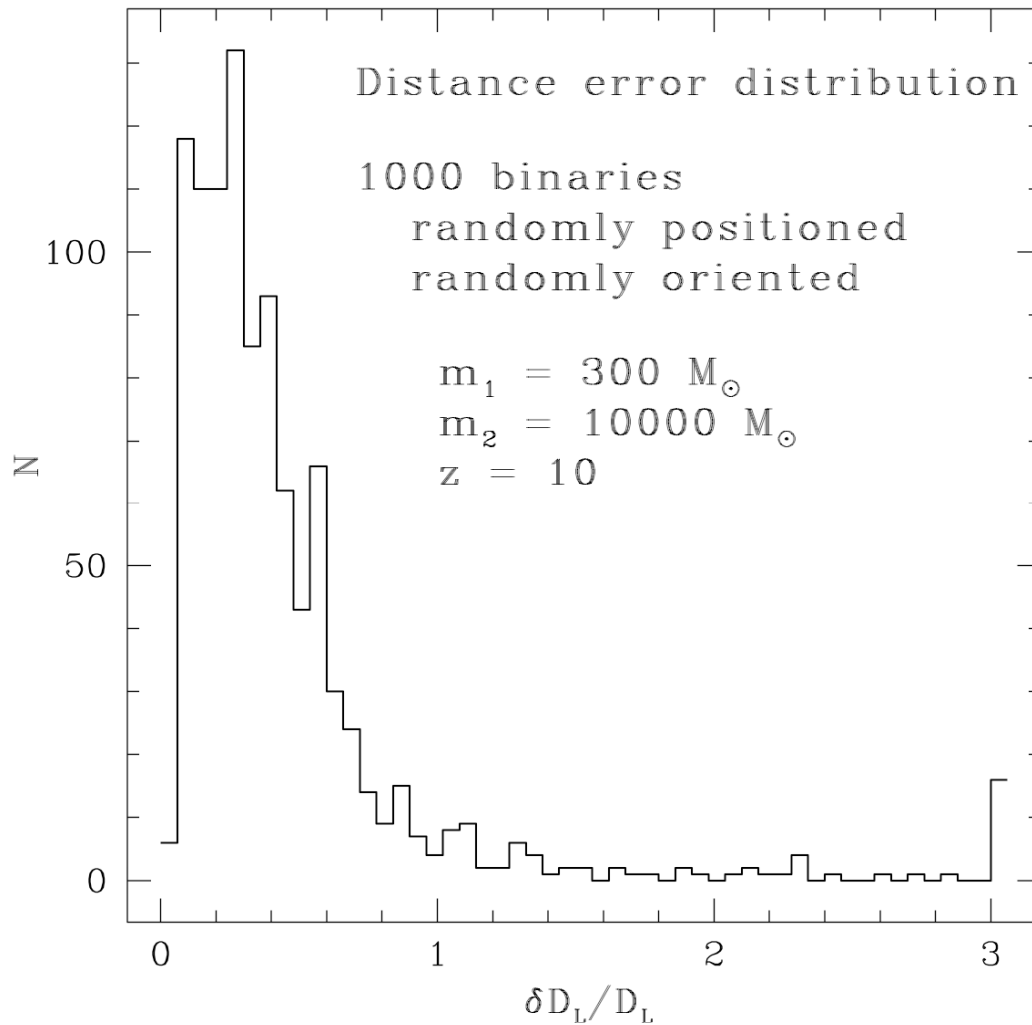
OR1.1: LISA shall have the capability to detect massive black hole binary mergers, with the larger mass in the range $10^4 M_\odot < M_1 < 10^5 M_\odot$, and a smaller mass of $M_2 = 300\text{--}1000 M_\odot$, at $z = 10$, with fractional parameter uncertainties of 35% for luminosity distance, 10% for mass and 20% for spin parameter at maximal spin. LISA shall maintain this detection capability for five years to improve the chance of observing some events.

Current estimates of luminosity distance and spin uncertainties (Hughes 2007a) for masses in these ranges at $z = 10$ are included in Table 4-2. The calculation is done following the procedures of Lang and Hughes (2006, cf §3.5). Redshifted mass uncertainties are determined well below the requirement ($\sim 1\%$), and are not shown. Values in the table show that the median performance meets the observation requirement in all 6 cases in the specified mass ranges, as well as in a number of others. Figure 4-1 illustrates the rate of improvement in parameter estimation for progressively smaller fractions of cases.

Table 4-2. Median values of fractional luminosity distance uncertainty, absolute spin parameter uncertainty, and SNR at $z=10$, assuming the standard noise model, a single interferometer, and randomly distributed position, orbital plane orientation, both spin orientations, and spin magnitude (uniformly distributed between 0 and 1). The spin uncertainty is absolute. These results provided courtesy of Scott Hughes (2007a).

M_1	M_2	D_L Uncertainty	Spin Uncertainty	SNR
1.00E+04	3.00E+02	31.90%	0.012	10.80
	1.00E+03	34.10%	0.029	18.50
	3.00E+03	43.20%	0.070	30.90
	1.00E+04	41.10%	0.115	47.90
3.00E+04	3.00E+02	28.50%	0.005	14.90
	1.00E+03	26.80%	0.008	26.40
	3.00E+03	25.00%	0.016	45.30
	1.00E+04	24.20%	0.041	79.50
1.00E+05	3.00E+02	31.70%	0.005	14.60
	1.00E+03	23.30%	0.006	27.80
	3.00E+03	20.20%	0.008	46.00
	1.00E+04	19.30%	0.020	75.00
3.00E+05	3.00E+03	22.50%	0.016	10.20

Figure 4-1 Histogram of cases for luminosity distance determinations with $M_1=10^4 M_\odot$ and $M_2=300 M_\odot$ at $z=10$. These results provided courtesy of Scott Hughes (2007a).



4.1.2 Search for the remnants of the first (Population III) stars through observations of intermediate-mass black hole captures, also at later epochs

Regardless of whether they are part of the growth history of the MBHs found at the centers of galaxies ($M > 10^6 M_\odot$) or not, some of the first stars may have collapsed to form IMBHs which then grew further. Binaries containing IMBHs may form either in stellar clusters (IMBH-IMBH binaries) or in the course of the hierarchical assembly of pre-galactic structures (IMBH-MBH binaries) (Miller and Colbert 2004). This investigation aims to bound the event rate for merging IMBH-IMBH and IMBH-MBH binaries early in the era of galaxy formation ($z \sim 6$), and in the event of detection,

explore the characteristics of such mergers. IMBH-MBH mergers at later times are addressed in §4.3.2. Even a single detection would confirm the existence of the elusive black holes in this mass range, if their existence has not already been confirmed in other ways.

LISA can detect gravitational waves from IMBHs spiraling into more massive companions in pre-galactic and galactic nuclei. When the mass ratio of the pair is $m_2/m_1 \sim 10^{-3} - 10^{-2}$ these sources are referred to as “intermediate mass-ratio inspirals” (IMRIs). Detection of IMRIs at $z < 6$, when more of the MBHs have grown larger, will help in understanding how, and how often, IMBHs were formed. Detection of such IMRIs will provide information on the mass function of Population III stars, the growth, dynamical evolution, and fate of their remnants, and other mechanisms for forming IMBHs, such as core collapse of globular clusters.

The instrument sensitivity model obtains a maximum reach of about $z \sim 30$ for a $10^4 M_\odot$ IMBH spiraling into a $3 \times 10^4 M_\odot$ MBH with $SNR = 10$. The masses could be estimated to $\sim 1\%$, but the distance would be essentially undetermined. Detections like this could provide limited information about the frequency of IMBHs merging with proto-galaxies, and sense the largest spatial volume. However, the observation requirement for IMBH binaries in this science investigation is set to $z = 6$ in order to extract spin and distance information that will illuminate the formation processes.

OR1.2: LISA shall have the capability to detect gravitational waves emitted by binaries consisting of at least one IMBH with mass $> 3 \times 10^2 M_\odot$ out to $z = 6$ with fractional parameter uncertainties of 33% for luminosity distance, 10% for mass and 20% for spin parameter at maximal spin. LISA shall maintain this detection capability for a 3 yr observing period to improve the chance of observing some events.

Table 4-3 demonstrates that the sensitivity model meets OR1.2 at $z = 6$ for $M_1 \geq 10^4 M_\odot$. Rough calculations suggest that the instrument sensitivity model also meets the requirement for smaller masses down to but excluding the case where both masses are $3 \times 10^2 M_\odot$. Table 4-2 illustrates that the sensitivity is not adequate for a similar requirement at $z = 10$.

4.2 Trace the growth and merger history of MBHs and their host galaxies

Massive black holes are essential components of galaxies, and their evolutionary states appear to be closely linked to those of their hosts. The available data show a tight correlation between black hole mass and the stellar velocity dispersion of the host bulge (Gebhardt et al. 2000; Ferrarese & Merritt 2002; Tremaine et al. 2002). In elliptical and spiral galaxies, the bulge velocity dispersion appears to correlate tightly with the value of the circular velocity measured at distances of 20-80 kpc from the center, suggesting that the mass of nuclear black holes correlates with the mass of the host dark matter halos (Ferrarese 2002). The association between MBHs and their host galaxies suggest a common evolutionary path and implies that MBHs are tracer

particles of their surrounding mass concentrations of baryons and dark matter (Silk & Rees 1998; Haehnelt & Kauffmann 2000; Adams, Graf, & Richstone 2001; Murray, Quataert, & Thompson 2005; McLaughlin, King, & Nayakshin 2006). The merger rates of MBHs as a function of cosmic time can then be used to constrain the mass assembly history of their host galaxies.

4.2.1 Determine the relative importance of different MBH growth mechanisms as a function of redshift.

A comparison of the current mass density in supermassive black holes with the energy emitted by active galactic nuclei indicates that most of the black hole mass was accumulated via radiatively efficient accretion of gas (Soltan's 1982 argument; Yu & Tremaine 2002; Hopkins et al. 2006). Very little information, however, exists today on $< 10^7 M_{\odot}$ MBHs to which LISA will be most sensitive. These holes may grow by radiatively efficient or inefficient disk accretion, by mergers with compact objects or stars, or by any combination of these. There are theoretical suggestions that black hole mergers may dominate the early growth phase (Islam, Taylor, & Silk 2003). Disk accretion typically leads to efficient spin-up of the growing hole, and produces rapidly spinning MBHs unless the feeding is "chaotic" (Volonteri et al. 2005; King & Pringle 2006). Black hole mergers do not lead to systematic effects, but simply cause MBHs to random-walk around the spin parameter they had at birth (Hughes & Blandford 2003). Rapidly spinning holes with high radiative efficiencies may satisfy Soltan's constraint. Large radiative efficiencies, however, slow down the black hole growth rate and make it difficult to build up $3 \times 10^9 M_{\odot}$ supermassive holes in less than 0.9 Gyr – as required by the luminous *Sloan Digital Sky Survey* quasars with redshift above 6 – from small initial seeds (Shapiro 2005; Volonteri & Rees 2005).

Observations of MBH masses, spins, binary mass ratios, and merger rates will therefore provide crucial information on the relative roles of accretion and mergers in massive black hole growth.

OR2.1: LISA shall have the capability to detect massive black hole binary mergers, with the larger mass in the range $3 \times 10^4 M_{\odot} < M_1 < 3 \times 10^5 M_{\odot}$, and a smaller mass in the range $10^3 M_{\odot} < M_2 < 10^4 M_{\odot}$, at $z = 10$, with fractional parameter uncertainties of 25% for luminosity distance, 10% for mass and 10% for spin parameter at maximal spin. LISA shall maintain this detection capability for five years to improve the chance of observing some events.

Current estimates of luminosity distance and spin uncertainties for most of this range of masses at $z=10$ are given in Table 4-2 (cf §3.6). Redshifted masses are, again, determined well below the requirement ($\sim 1\%$), and are not given. Values in the table show that the median performance meets the observation requirement for all but one case shown. Sources with better than the median parameter estimation will satisfy that one case in slightly less than 50% of the time. The median performance also meets the observation requirement for the two cases not shown. Sources somewhat beyond $z=10$

with better than the median parameter estimation may also satisfy the parameter uncertainties in the observation requirement.

The remnant's spin parameter is best measured via observation of its ringdown following merger (Dreyer et al. 2004). The ringdown carries away 1% of the remnant black hole rest mass (Laguna 2006 private communication). With this efficiency LISA can detect and measure the spin parameter for remnant black holes in the mass range $3 \times 10^4 M_{\odot} < M < 3 \times 10^5 M_{\odot}$ at redshifts up to $z = 10$ (Finn 1992).

4.2.2 Determine the merger history of 10^4 to $3 \times 10^5 M_{\odot}$ MBHs from the era of the earliest known quasars ($z \sim 6$)

Models of hierarchical structure assembly predict that the first stars and MBHs formed in sub-galactic scale dark matter halos at $z > 15$. LISA observations of MBH coalescences from these epochs will open a new window in probing the formation and evolution of early cosmic structure. MBHs in the range 10^4 to $3 \times 10^5 M_{\odot}$ will be hosted by low-mass proto-galaxies: some current models of MBH formation and assembly predict tens of detectable binary coalescences per year at redshifts $z \sim 15$ or so (Sesana et al. 2004) around and prior to the reionization epoch. These event rates may discriminate between different competing scenarios for the end of the dark ages and the birth of the first luminous sources.

This investigation requires knowledge of mass, luminosity distance and spins for each observed merger event in the redshift range $3 < z < 15$. For parts of the mass range the instrument sensitivity will reduce useful detections beyond $z=10$ to only the more favorable conditions. Binaries with a larger mass of $3 \times 10^6 M_{\odot}$ and smaller masses above $1 \times 10^4 M_{\odot}$ will spend at least part of the year before coalescence below 0.03 mHz, thus reducing their integration time.

OR2.2: LISA shall have the capability to detect massive black hole binary mergers, with one mass in the range $10^4 M_{\odot} < M_1 < 3 \times 10^5 M_{\odot}$ at $z = 6$, with fractional parameter uncertainties of 33% for luminosity distance, 10% for mass and 20% for spin parameter at maximal spin.

Current estimates of luminosity distance and spin uncertainties for most of this range of masses at $z=10$ can be found in Table 4-2. As with previous requirements, redshifted masses are determined well below the requirement ($\sim 1\%$), and are not given. Values in the table show that the median performance meets the observation requirement for 10 of the 13 cases shown. In the three cases where the median performance does not meet the luminosity requirement, the requirement will be fulfilled by the fewer events with more favorable parameter estimation. Sources somewhat beyond $z=10$, where parameters can be estimated with better than the median parameter performance, may also satisfy the parameter uncertainties in the observation requirement. Masses in this range, and below at $z < 6$ will, of course, generally be visible with good parameter estimation.

Table 4-3 illustrates the degree to which the standard instrument noise model permits the estimation of parameters for smaller redshifts than 10. In this table for $z=6$, the performance of the standard instrument model meets the conditions of the observation requirement – and in 10 of 12 cases substantially exceeds it.

Table 4-3. Median values of fractional luminosity distance uncertainty, absolute spin parameter uncertainty, and SNR at $z=6$, assuming the standard noise model, a single interferometer and randomly distributed position, orbital plane orientation, both spin orientations, and spin magnitude (uniformly distributed between 0 and 1). The spin uncertainty is absolute. These results provided courtesy of Scott Hughes (2007a).

M_1	M_2	D_L Uncertainty	Spin Uncertainty	SNR
1.00E+04	3.00E+02	17.40%	0.009	12.70
	1.00E+03	22.80%	0.022	22.60
	3.00E+03	31.30%	0.057	37.20
	1.00E+04	31.00%	0.069	61.40
3.00E+04	3.00E+02	16.70%	0.003	18.60
	1.00E+03	17.00%	0.006	33.00
	3.00E+03	15.10%	0.004	56.50
	1.00E+04	17.30%	0.009	95.10
1.00E+05	3.00E+02	17.80%	0.003	22.90
	1.00E+03	14.90%	0.003	42.40
	3.00E+03	11.80%	0.010	72.10
	1.00E+04	11.40%	0.026	124.00

4.2.3 Determine the merger history of 3×10^5 to $10^7 M_\odot$ MBHs at later epochs ($z < 6$)

Active galactic nuclei powered by supermassive black holes keep the universe ionized at $z < 6$, control the structure and thermodynamics of the intergalactic medium, and regulate star formation in their host galaxies. This epoch includes the peak of quasar activity and at this epoch the evidence for MBH–galaxy coevolution is very strong.

It is understood that, following the merger of two massive galaxies, a bound MBH binary will form, shrink due to three-body-interactions with background stars (gravitational slingshot) or gas dynamical processes, and ultimately coalesce by emitting a burst of gravitational waves (Begelman et al 1980; Kazantzidis et al. 2005; Escala et al. 2004). But the sequence and timing of the events leading to the formation of a bound black hole pair and its orbital decay have remained unclear (the “final parsec problem,” Milosavljevic & Merritt 2003).

Since all bright galaxies at these redshifts appear to host MBHs, LISA will detect all galaxy mergers that ultimately lead to the coalescence of $< 10^7 M_\odot$ MBHs. These are the strongest sources in the LISA band, making precise measurements of system parameters possible (Lang and Hughes 2006). The determination of sky position to a

few arc minutes together with the luminosity distance to 0.1% will facilitate the search for electromagnetic counterparts of the merger event among the $\sim 10^4$ galaxies in the error box. Even a few identifications and redshifts will permit precision measurements of the cosmic expansion history, geometry, and dark energy density (see Section 4.6.1 below).

At redshifts and masses in this range, the principle limitation of the standard noise model is the low frequency cutoff. Larger masses at larger redshifts make signals at frequencies too low for enough integration. In general, the parameters of an MBH binary, involving two black holes with masses $\geq 10^3 M_\odot$, can be well determined whenever the signal is above 0.1 mHz for a year prior to coalescence.

This investigation needs to:

- Determine accurate component masses and spin parameters, orbital eccentricity, and luminosity distance,
- Determine the ratio of the binary's reduced to total mass with a fractional accuracy of at least 10% for $\mu/M < 0.1$,
- Determine the luminosity distance for an equal mass system, with component masses $(1+z)M = 10^6 M_\odot$, with a fractional accuracy of better than 30% (Berti et al 2005a).

OR2.3: LISA shall have the capability to detect massive black hole binary mergers of systems with $M_1 < 3 \times 10^5 M_\odot$ and $M_2 \leq 10^3 M_\odot$ at $z=6$, , and $M_1 \leq 10^7 M_\odot$ and $M_2 \leq 1 \times 10^4 M_\odot$ at $z = 3$ with fractional parameter uncertainties $\leq 20\%$ for luminosity distance, 5% for mass and 10% for spin parameter at maximal spin. LISA shall maintain this detection capability for 5 years to anticipate a sample of greater than 5 merger events with components in the $10^5 - 3 \times 10^6 M_\odot$ range at a distance of $z=2$ (based on the estimates of Sesana et al. 2004).

Table 4-3 illustrates the degree to which the standard instrument noise model permits the estimation of parameters at $z=6$. The performance of the standard instrument model meets the conditions of the observation requirement in 9 of 12 cases, based on the median standard; only the better-determined sources will suffice in the remaining 3 cases. Table 4-4 illustrates the performance at $z=3$.

Table 4-4. Median values of fractional luminosity distance uncertainty, absolute spin parameter uncertainty, and SNR at $z=3$, assuming the standard noise model, a single interferometer and randomly distributed position, orbital plane orientation, both spin orientations, and spin magnitude (uniformly distributed between 0 and 1). These results provided courtesy of Scott Hughes (2007a).

M_1	M_2	D_L Uncertainty	Spin Uncertainty	SNR
3.00E+04	1.00E+03	7.90%	0.30%	48.80
	3.00E+03	8.60%	0.60%	79.10

3.00E+05	1.00E+03	7.10%	0.10%	64.80
	3.00E+03	5.90%	0.10%	108.00

4.3 Explore stellar populations and their dynamics in galactic nuclei

LISA can detect gravitational waves from compact objects spiraling into the central massive black holes in galactic nuclei. For the purposes of exploring the stellar populations in galactic nuclei, and their dynamics, it is useful to divide the possible sources into two classes by the ratio of mass of the inspiraling object to that of the central massive black hole.

Sources where the ratio of the smaller mass to the larger mass is very small $M_2/M_1 \sim 10^{-6} - 10^{-5}$ are referred to as “extreme mass-ratio inspirals” (EMRIs). In these cases, the smaller component will be a compact object, either a white dwarf, a neutron star, or a stellar-mass black hole (BH). Three scenarios for producing these binary systems in the vicinity of the central MBH have been suggested, and will be discussed in §4.3.1 below.

Sources where the mass ratio lies in the range $10^{-5} < M_s/M_L < 0.01$ are called “intermediate mass-ratio inspirals” (IMRIs). In these cases, the inspiraling object is an intermediate-mass BH with mass in the range of $10^2 M_\odot < M_2 < 10^4 M_\odot$; the mass ratio is $M_s/M_L \sim 10^{-3} - 10^{-2}$. Detections of EMRIs and IMRIs will reveal information about the stellar population in the close vicinity of the MBHs.

4.3.1 Characterize the immediate environment of MBHs in $z < 1$ galactic nuclei from EMRI capture signals

At least three distinct channels for producing EMRIs have been pointed out in the literature, and this multiplicity of channels increases confidence that at least one of them will lead to a significant rate. The oldest and best understood idea is that two-body encounters in the inner ~ 0.01 pc send one of the stellar-mass objects into highly eccentric orbits, with pericenter ~ 10 Schwarzschild radii from the MBH, after which gravitational radiation reaction drives inspiral into the MBH. Among the important physical processes setting the rate for this channel are mass segregation and resonant relaxation. Other proposed channels are tidal disruption of binaries that pass close to the MBH (Miller et al. 2005) and creation of massive stars in accretion disks surrounding MBHs with their concomitant rapid evolution into compact objects (Levin 2006).

It should be possible to observationally distinguish between the different channels, at least in a statistical sense: EMRIs resulting from 2-body encounters should have roughly random orbital orientations and can remain moderately eccentric right up until the final plunge. Objects tidally torn from binaries should have very low eccentricity (by the time they enter the LISA band) but roughly arbitrary inclination angle between

their orbital plane and the MBH spin. Compact objects created in the accretion disk should have very low eccentricity and orbital angular momentum nearly aligned with the spin of the MBH.

The EMRI observation requirements below are set somewhat conservatively, because the event rate for EMRIs is still quite uncertain. White dwarfs, neutron stars, and stellar-mass black holes are all potential EMRI sources (i.e., all plunge through the MBH horizon before being tidally disrupted. The best current estimates suggest that inspirals of $\sim 10 M_{\odot}$ BHs will dominate the LISA detection rate (Hopman 2006). The reasons are two-fold: mass segregation in the galactic nucleus concentrates heavier stars towards the center, and $10 M_{\odot}$ BHs can be detected ~ 10 times further away than $0.6 M_{\odot}$ WDs (based on comparing the SNRs for the last 3 years of inspiral), so the volume of space in which they can be detected is $\sim 10^3$ times larger.

The best current estimate is that the BH inspiral rate in the Milky Way is $2.5 \times 10^{-7} / \text{yr}$ (Hopman 2006). Extrapolating this rate out to $z=1$, Gair et al. (2004) show that signals with $SNR > 30-35$ should be detected at the rate of $\sim 50-100$ EMRIs per year with standard LISA noise and response function and two interferometers, or $\sim 20-40/\text{yr}$ with one interferometer. However, there are a number of uncertain ingredients in the overall rate calculation. The space density of $10^6 M_{\odot}$ BHs and the stellar mass function in galactic nuclei are both poorly known. These uncertainties argue for the full sensitivity of the reference instrument noise model. Recall that raising the noise curve by a factor 2 decreases the detection rate by a factor ~ 8 .

For EMRIs involving stellar mass black holes, most of the SNR accumulates in the last ~ 2 years of inspiral, corresponding to $\sim 200,000$ observable gravitational wave cycles. The EMRIs signals will typically be buried in noise (both instrumental noise and confusion noise from white-dwarf binaries), but it will be possible to dig the EMRI signals out of the noise using matched filtering. Due to the huge number of independent templates required to cover the space of waveforms, it has been estimated that the matched filtering SNR must be at least ~ 14 to yield a confident detection. However, again due to the vast number of templates, straightforward optimal matched filtering over the entire parameter space will not be computationally feasible. So sub-optimal methods will be required. The best current estimate is that an SNR of 30-35 will be required for detection, with realistic computing power (Gair et al. 2004).

Note that accurately determining the source parameters (including distance) from EMRIs comes almost automatically with the ability to detect EMRIs at all. They come because of the great predictability of the waveforms, the high number of detected GW cycles, and the relatively high SNR (~ 50). That is, they do not entail significant measurement performance beyond the capability just to detect these sources, and so come “at no extra charge.” Therefore the observation requirements below are mostly just set by overall sensitivity (including to a range of MBH masses).

Also, determining the MBH spins will significantly constrain their accretion and merger history. Large spins suggest a long period of disk accretion, while low spin suggests mass buildup through mergers.

This investigation will:

- Determine precise masses and spins for a substantial sample of quiescent galactic black holes
- Determine the relative importance of different EMRI channels from the distribution of observed eccentricities and inclination angles
- Constrain the stellar environment of the central star clusters around massive black holes, by making use of the observed rates, masses of EMRIs, and correlations with central black hole mass.

OR3.1: LISA shall have the capability to detect gravitational waves emitted during the last year of inspiral for a $10 M_{\odot}$ black hole orbiting a $10^{6 \pm 0.25} M_{\odot}$ black hole at $z=1$ with $SNR > 30$ (averaged over source locations and orientations) with a single interferometer. LISA shall maintain this detection capability for a 3 yr observing period.

Calculations by Gair et al. (2004) estimate that the standard noise and response model just satisfies this criterion. EMRI detection requires the full sensitivity in the range ~ 1 -10 mHz, where the SNR accumulates.

The 3-yr observation period comes partly from the uncertain rate, and partly from “edge effects”: the first ~ 8 months of observation will yield very few EMRI detections, since not enough SNR could have built up in this time. An observation time of at least 3 years is necessary to keep the fractional loss of sources to “edge effects below” $\sim 20\%$.

4.3.2 Study intermediate-mass black holes from their capture signals

Observational evidence of intermediate-mass black holes (10^2 - $10^4 M_{\odot}$) comes from ultraluminous X-ray sources not associated with galactic nuclei and from the stellar dynamics of globular clusters. Stellar dynamics modeling shows that a black hole of several hundred solar masses can form and grow in young massive star clusters. Miller and Colbert (2004) have summarized the evidence for, and the outstanding questions about, these objects. When the cluster sinks to the center of the galaxy, the IMBH could become a source of gravitational radiation by merging with the nuclear supermassive black hole (Miller 2005). In this scenario, the source would be the IMBH and a supermassive black hole in a galactic nucleus. This investigation will determine the event rate and characteristics of these mergers.

Since SNR for EMRIs and IMRIs scales as the square root of the smaller mass, IMRIs have roughly 3-30 times higher SNR than $10 M_{\odot}$ EMRIs, at the same distance. However, the inspiral rate for IMRIs is much less well understood than for EMRIs,

and is presumably considerably lower. Miller (2005) estimates a few to tens of LISA detections per year for both scenarios.

The various hierarchical merger models in Sesana et al (2007) predict that most mergers involving $10^6 M_{\odot}$ MBHs, like those found in fully-formed galactic nuclei, only begin in appreciable numbers after $z \sim 6$, and peak at $z = 2$. Consequently, a redshift of 3 is chosen for the observation requirement on IMBHs merging with supermassive black holes.

OR3.2: LISA shall have the capability to detect gravitational waves emitted by a $10^2 - 10^4 M_{\odot}$ IMBH spiraling into an MBH with mass M in the range $3 \times 10^5 - 1 \times 10^6 M_{\odot}$ out to $z=3$ (with SNR ~ 30). LISA shall maintain this detection capability for a 3 yr observing period.

Based on available calculations (Cutler 2007) the instrument sensitivity model appears to meet OR3.2. However, this is to be confirmed (**TBC**) with a calculation of parameter uncertainties known to be robust for mass ratios $\sim 10^{-4}$, circular orbits and spin/precession effects. Highly elliptical orbits and precession effects generally improve parameter estimation, sometimes very substantially.

4.3.3 Improve our understanding of stars and gas in the vicinity of galactic black holes using coordinated gravitational and electromagnetic observations

Identification of electromagnetic emission from gas around the black holes whose properties LISA measures is exciting both for the rich tests this would enable of models of the behavior of gas around black holes, and for the opportunity it offers to identify the redshift of the source, and thus enable precision cosmography [cf §4.6.1]. Three scenarios in which this might happen are: (1) the onset of accretion after the merger of an MBH binary, (2) emission from a circumbinary disk disturbed by the mass loss of a merger, and (3) tidal disruption of a captured star in the late stages of an EMRI event.

A binary of comparable mass black holes ($M_2/M_1 > 0.01$) in a galactic nucleus will attract and accumulate gas in a circumbinary disk. The binary's varying gravitational potential supplies energy and angular momentum to the disk, largely preventing accretion until after the merger (Milosavljevic & Phinney 2005, MacFadyen & Milosavljevic 2006) when the disk will be able to fill in on a timescale of 1-10 years (depending on disk mass and viscosity), and an AGN would turn on, bright enough to be detected by current and planned X-ray satellites (Milosavljevic & Phinney 2005, Dotti et al 2006). Observation of this AGN would offer the unique opportunity to unambiguously and precisely measure the mass and spin of the remnant black hole and compare with the mass and spin inferred from traditional modeling of electromagnetic emission from AGN (e.g. QPO models, line widths of broad optical emission lines, X-ray Fe-K shell fluorescence).

To identify the source galaxy with an electromagnetic observation, the sky location and redshift must be localized well enough that the field can be monitored in the optical-UV-Xray bands, and the new AGN distinguished from other large-amplitude variable sources. Depending on mass and redshift, the sky location must be determined to degree scales and the distance to a precision of 10% (cf. Kocsis et al 2006). Note that if the event can be localized ~ 4 days before merger, one could hope also to get pre-merger images, which would make any case more convincing

In addition to this afterglow AGN, there may well be emission within minutes to days after merger from acoustic and shock waves excited in the circumbinary disk by the sudden loss of about 4% of the mass through gravitational radiation of mass-energy in the final coalescence and ringdown (Phinney et al. 2007). This would be most readily detected in the rest-frame UV (optical at earth for $z > 1$) by wide field synoptic survey telescopes such as LSST, and would enable the first precise determination of the internal structure of accretion disks around the black holes in galactic nuclei.

To ensure that at least one merger can be observed during a clear night in the hemisphere accessible to LSST, LISA should localize ~ 10 sources to within the 3.5 degree LSST field with enough notice (~ 2 days) to enable pre-merger deep fields to be observed and rescheduling of the telescope during and immediately after the merger.

For mass ratios < 0.01 , matter can more efficiently 'leak' from the circumbinary disk onto the black holes, and the accretion rate may become highly enhanced even before the merger (Armitage & Natarayan 2002). EMRI events involving helium stars, low mass white dwarfs, and brown dwarfs (the latter in the local group only) can lead to tidal disruption of the captured star in the late stages of the EMRI event (Kobayashi et al 2004). As with other proposed tidal disruption events (cf. Komossa et al 2004, Gezari et al 2006), the aftermath would be an ultraviolet-X-ray flare, but with the unique feature that the masses, spins and initial orbit will have been precisely defined by the gravitational wave measurement. Success here would require localization during the EMRI event to within the field of view of whatever UV and soft X-ray telescopes are flying at the time.

The localization requirements here are the same as those in §4.6.1 and are repeated for completeness, but without the accompanying discussion and figures. See §4.6.1 for a more complete rationale of the requirements. The observational requirements for this investigation are divided into three parts: pre-merger localization (OR3.3.1) and post-merger localization (OR3.3.2) of massive black hole mergers, and localization of EMRI events (OR3.3.3).

OR3.3.1: LISA shall be capable of providing advance warning and localization of mergers of $0.5\text{--}3 \times 10^6 M_{\odot}$ black holes at $z=1$ with an accuracy of less than 15 square degrees one week before merger.

OR3.3.2: LISA shall be capable of localizing the source direction to better than 1 square degree within one week after merger, and with uncertainties of less than 1% in

the luminosity distance for black holes at $z=1$ with component masses in the range $M(1+z) = 10^{5-6} M_{\odot}$ and mass ratio $r > 3$.

OR3.3.3: LISA shall have the capability to measure distance to EMRI or IMRI sources with $\text{SNR} > 50$ to 3% or better with a sky position better than 5 square degrees.

4.4 Survey compact stellar-mass binaries and study the morphology of the Galaxy

Very many compact stellar mass binaries in the Milky Way and its surroundings will be bright in gravitational radiation. Those detectable by LISA will be strongly dominated by white dwarf binaries, but will also contain neutron star systems and possibly stellar-mass black holes. LISA will therefore provide a radically new arena for studies of the formation and evolution of such exotic objects, the physical mechanisms (radiation reaction, tidal effects and mass transfer/loss) that drive their orbital evolution, and new insights on the white dwarf internal structure and, possibly, the formation scenario of supernovae Type Ia. This class of binaries is electromagnetically very faint (or even silent) and LISA will increase the observational sample 10-fold. Unlike electromagnetic observations that are biased against short orbital periods, LISA is best suited to detect tight systems. The LISA stellar mass binary sample will therefore be complementary to the electromagnetic one. In addition, simultaneous observations with electromagnetic and astrometric surveys will enable otherwise unobtainable measurements of masses, distances, stellar sizes, tidal effects and mass transfer.

At the low-frequency end of LISA's expected sensitivity (below ~ 1 mHz), the gravitational wave signals from Galactic compact binaries will overlap to the extent of producing a confusion-limited foreground from tens of millions of binaries in the relevant frequency range. Foreground radiation from extra-galactic white dwarf binaries will also be present and potentially observable above ~ 2 mHz (Hils et al, 1990; Farmer and Phinney, 2004). LISA will statistically reconstruct the distribution of these sources in the Galaxy, test models of binary evolution and constrain the star formation rate by measuring the spectral shape of the foregrounds. [Note that any spectral continua not of cosmological origin is referred to as a 'foreground' in this section.]

4.4.1 Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground

LISA will discover at least a few thousand, previously unknown, stellar-mass binaries within the Milky Way (Evans et al 1987, Hils et al 1990, Nelemans et al 2001), associated globular clusters (Benacquista et al 2001), and nearby satellite galaxies (Cooray and Seto 2005). The number of detected systems as a function of the binary period can be used to determine the formation rate and the evolutionary history of the population. Observations of binaries in stellar clusters may provide a signature of

different evolutionary channels (Benacquista et al 2001) and observations of double neutron stars may provide a new means, complementary to electromagnetic observations (e.g. radio pulsar observations) and the likely ground-based GW observations, to quantify their formation rate.

Information on the evolutionary history of the Galactic population of compact stellar-mass binaries is also encoded in the spectrum of the Galactic foreground radiation below a few mHz and the extra-galactic foreground which may become observable above 2 mHz (Hils et al, 1997; Farmer and Phinney, 2003), and which depends on the cosmological star formation rate and white dwarf binary evolution. LISA has therefore the capability of constraining these models, by exploiting the time variation of the Galactic foreground signal (Cornish, 2001; Ungarelli and Vecchio 2001, Edlund et al. 2005) and by discriminating between the instrumental noise and the isotropic component of the diffuse foreground using suitable TDI combinations. (Tinto et al, 2001; Hogan and Bender, 2001; Seto and Cooray 2004, Taruya and Kudoh 2005).

This investigation will:

- Quantify the birth rate and evolutionary history of stellar mass binary populations by discovering at least 1000 compact binaries (primarily white dwarfs, but including also a handful of neutron stars, and possibly stellar mass black holes), and including compact binary systems in globular clusters and the Magellanic Clouds
- Constrain the birth rate of Galactic white dwarf binary systems by measuring the spectrum of the Galactic foreground at frequencies below 1 mHz.
- Constrain the cosmological white dwarf binary formation rate by attempting to detect a background of extragalactic white dwarf binaries at frequencies of 2-5 mHz.

OR4.1.1: LISA shall have the capability to detect at least 1000 binaries at $SNR > 10$ with orbital periods shorter than approximately 6 hrs and determine their period, using a reference model of the galaxy (Nelemans et al 2001) for source strength and distribution. LISA shall maintain this detection capability for at least 1 year.

OR4.1.2: LISA shall have the capability to measure the spectral amplitude and frequency dependency of the unresolved Galactic foreground below 1 mHz and constrain the spectral amplitude of the unresolved extragalactic foreground in the frequency region 2-5 mHz. LISA shall have the means to discriminate between instrumental and environmental noise and the unresolved Galactic foreground and unresolved extragalactic foreground, when all three arms are operating.

Based on population synthesis models and observations (e.g. Nelemans et al, 2001; Nelemans et al, 2004), our current understanding predicts that LISA will individually resolve several thousand such systems within our Galaxy (Nelemans et al, 2001), the surrounding globular clusters (Benacquista et al, 2001), and nearby satellite galaxies (Cooray and Seto, 2005).

4.4.2 Determine the spatial distribution of stellar-mass binaries in the Milky Way and environs

The majority of stellar-mass binaries will be essentially monochromatic over the period of the LISA mission (Nelemans et al. 2001, Benacquista et al. 2004); nonetheless, several hundreds will show a significant frequency drift (Nelemans et al, 2001). For those, LISA may provide a 3D map (distance and sky location). In fact, measurements of the intrinsic change of gravitational wave frequency allows the "mass-luminosity distance" degeneracy to be broken (unless other effects, such as mass transfer and/or tides significantly alter the orbital evolution; e.g. Stroeer et al 2005), and one can simultaneously solve for both the chirp mass and the distance to the emitting binary. In the event that the frequency derivative is not measurable, simultaneous electromagnetic and/or astrometric observations of LISA-identified sources will provide additional information, such as distance and/or masses, to break the degeneracy (e.g., Nelemans et al 2004, Cooray and Seto 2005, Stroeer et al 2005).

Even in absence of distance measurements, LISA will still be able to produce a 2D map of binary populations in the Galaxy by determining the sky location of the whole LISA detected sample. Combining measurements from the diffuse foreground radiation and the resolved systems, LISA will produce a statistical assessment of the contributions to different Galactic components, such as the Galactic bulge with its bar, the disk and, in particular, the halo.

This investigation will:

- Measure the moments of the distribution of binaries in the Galaxy through the distribution of the Galactic foreground and the individually resolved binaries, including compact binary systems in globular clusters and the Magellanic Clouds and hence probe the structure of the Galaxy and its environs.
- Have the capability to identify the 3-dimensional distribution of at least a hundred binaries whenever the mass-distance degeneracy can be broken.

OR4.2: LISA shall have the capability to: (1) determine the position of at least a hundred sources with better than a square degree angular resolution and the frequency derivative to a fractional uncertainty of 10%; (2) measure the first two moments of the distribution of the Galactic unresolved foreground; and (3) measure the distance to 10% for the binaries for which an EM counterpart is available. LISA shall maintain this detection capability for at least 2 years.

The reference sensitivity and the detector motion will allow the instrument to reconstruct the source position in the sky using the frequency and amplitude modulations of the signals (e.g., Cutler 1998; Takahashi and Seto, 2001). Moreover, the Galactic foreground radiation is anisotropic as recorded by the LISA instrument (Cornish 2001, Ungarelli and Vecchio 2001, Seto 2004, Benacquista et al. 2004), and therefore the spatial distribution can be measured using the directional sensitivity of the antenna.

4.4.3 Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations

Gravitational wave measurements can provide complementary information about the evolution of ultra-compact binaries where tidal effects or mass transfer compete or even dominate the other physics driving the system evolution, enabling detailed studies of such processes. Measurements of the first and second gravitational wave frequency derivative provide a straightforward test of whether radiation reaction is responsible for the period evolution of the binary (Nelemans et al, 2004; Stroeer et al, 2005). However, much richer information can be gained if the masses can be determined. This requires electromagnetic observations of LISA detected sources if the period evolution is not determined solely by radiation reaction, highlighting the importance of coordinated gravitational wave and electromagnetic observations. There are a handful of “verification binaries” (such as RXJ0806, V407 Vul and AM CVn) as well as possibly many tens or hundreds currently unknown systems for which complementary electromagnetic observations will be possible (Cooray, Farmer and Seto, 2004, Nelemans et al, 2004). In this case, one can directly estimate temperature and age if broadband colors can be measured, and can even measure individual masses and radii if the system is eclipsing or if spectra can be taken.

This investigation will:

- Explore the influence of tidal coupling and mass transfer on the orbital period evolution of compact binaries, thus improving our understanding of the masses, internal structure, and orbital couplings in compact object binaries.
- Combine electromagnetic observations with gravitational wave observations whenever possible, to make direct measurements of a range of properties (e.g. temperature, masses, mass transfer rate, stellar radii) of specific systems.

OR4.3: LISA shall have the capability to measure the second frequency derivative of binary systems with gravitational wave frequencies above 20 mHz to 10% and their sky location to better than 0.1 square degree. LISA shall maintain this detection capability for at least 5 years.

In a one year observation, the reference sensitivity readily provides the capability to measure the second frequency derivation of a chirping source to 10%.

4.5 Confront General Relativity with observations

Einstein’s theory of gravity, General Relativity, contains no free parameters and so makes unambiguous predictions for the production of gravitational waves (from a given source model), their propagation through space and their influence on the trajectories of, and light propagation time between, the LISA sciencecraft. LISA’s

excellent sensitivity gives it the opportunity to test gravitation theory to high precision in situations not previously accessible to observation or experiment.

Observations of binary pulsars, especially of the classic Hulse-Taylor pulsar system PSR 1913+16 and the double pulsar system PSR J0737-3039A/B, give us great confidence that General Relativity describes gravity accurately enough for LISA to observe and measure gravitational waves. The gravitational waves emitted by known binary pulsars are near the lower end of the LISA frequency band, (~ 0.1 mHz), and the orbital period derivatives for the binary pulsars are consistent with energy loss to gravitational radiation as predicted by general relativity, to within the $\sim 1\%$ error bars of the measurements. These and Solar System measurements give considerable confidence that General Relativity is at least close to correct, at macroscopic scales.

Nevertheless, just as the precession of Mercury's perihelion revealed a flaw in Newton's theory of gravity, so it is important to confront General Relativity with observations, and search for any discrepancies. When LISA observes the mergers of two massive black holes, it will be observing the effects of gravity in a strong-field, highly dynamical regime that has yet not been probed. Since the SNR for the strongest such events will be $\text{SNR} \sim 10^3$, one will be able to observe the fine details of the emitted waveforms, roughly a hundred times more accurately than will be possible from the ground with any other sources. When LISA observes EMRIs, stellar-mass compact objects spiraling into MBHs, it will be able to effectively map out the spacetime of the MBH. By comparing these observations with the predictions of general relativity theory, LISA can look for deviations that may not even be modeled by existing alternative theories.

LISA has unique advantages in making these observational tests. First, gravitational radiation propagates through the Universe without scattering or absorption. One does not have to model corrections for propagation effects before using the observations to test fundamental theory. Second, many of LISA's sources are "clean", i.e. they consist of black holes or objects so compact that their internal structure is not needed in the source model. It is only possible to test a theory if the other properties of the system being observed are well under control. Black holes are the ideal system for performing such tests.

4.5.1 Detect gravitational waves directly and measure their properties precisely

This investigation will directly determine whether waves such as those predicted by Einstein propagate away from dynamic, massive objects and whether they interact with test bodies in the way described by General Relativity. This observation of the gravitational wave signal from the inspiral of two compact objects with the LISA constellation will test the predictions of General Relativity over 1.5 decades in orbital frequency, terminating in the highly relativistic regime near coalescence.

The investigation yields two requirements: direct detection of gravitational waves from one or more white-dwarf binary systems in the galaxy (OR5.1a) and detection of

gravitational waves from the inspiral, ringdown, and merger of MBH binaries (OR5.1b).

Direct detection of gravitational waves from compact white-dwarf binary systems in the galaxy. By the time LISA is launched, it is expected that numerous compact white dwarf binary systems will be known whose orbital period, distance and other system parameters such as masses will be measured. These systems will be detectable by LISA in weeks to months and can be used to verify LISA performance. The corresponding requirement is

OR5.1.1: LISA shall have capability to detect and study 3 or more optically observable verification binaries between 1 and 10 mHz with $SNR > 20$ in 2 years of mission lifetime.

This requirement is easily satisfied by the nominal LISA sensitivity performance.

Detection of gravitational waves from the coalescing MBH binaries. LISA must be capable of detecting the inspiral, ringdown, and merger signals from coalescing MBH binaries with sufficient SNR to compare measured waveforms to predictions.

OR5.1.2: LISA shall be capable of observing the gravitational waves from at least 50% of all $z \sim 2$ coalescing binary systems consisting of compact objects with masses between 1 and $10 \times 10^5 M_{\odot}$ and mass ratios between 1:1 and 1:3. LISA shall detect these systems with $SNR \geq 5$ in each of 5 equal logarithmic frequency bands between 0.03 mHz (or the lowest observed frequency) and the highest inspiral frequency

LISA satisfies this requirement assuming a standard noise model and a single interferometer as can be verified by conventional calculations using the strain signal from the binary inspiral phase of a MBH binary.

4.5.2 Test whether the central massive objects in galactic nuclei are the black holes of General Relativity

The central massive objects known to exist in the centers of most galaxies are presumed to be black holes. LISA can uniquely confirm that these objects are black holes and at the same time validate the predictions of general relativity that all vacuum black holes are described by the Kerr metric. We adopt the operational definition that the spacetime contains a black hole if it contains an event horizon. By observing whether the radiation from EMRI objects terminates when they reach the expected location of the horizon, LISA will determine whether or not the spacetime contains a horizon and hence whether the central objects are black holes. If they are black holes, then the details of the phase and polarization of the waves emitted by EMRIs contain information that can be used to determine whether the metric outside the horizon has the properties of the Kerr metric, and in particular whether all aspects of the geometry are fit by just the two Kerr parameters of mass M and angular momentum J . This is a test of the famous no-hair theorem of black holes (Israel 1967).

This science investigation will test whether astrophysical black holes exist with the properties predicted by general relativity and whether highly relativistic EMRI waveforms are consistent with predictions of General Relativity. Any observations of IMRI events will also contribute to these science goals. And, it will use EMRIs to measure the mass quadrupole of the central moment, and compare to the predictions of the BH no-hair theorem.

OR5.2: LISA shall have the capability to detect gravitational waves emitted during the last year of inspiral for a $10 M_{\odot}$ black hole orbiting a $3 \times 10^5 - 3 \times 10^6 M_{\odot}$ black hole at 1 Gpc with $SNR > 30$. LISA shall have a science mission duration with adequate observation time for EMRIs to sweep over a range of r/M to map space-time, and to provide a good sample of events.

The SNR obtained by LISA for $10 M_{\odot}$ black hole into a $3 \times 10^5 M_{\odot}$ black hole and a $3 \times 10^6 M_{\odot}$ black hole at 1 Gpc were calculated in the LIST Working Group 1 EMRI Taskforce Report (2003). Table 4-5 shows that for nominal LISA noise performance, $SNR > 30$ is achieved for a single interferometer (X) and the relevant mass for observation times of at least one month or longer.

Table 4-5 Signal-to-noise estimates for Extreme Mass Ratio Inspiral events at 1 Gpc assuming baseline LISA, optimistic WD subtraction (5 yr), and volume-inclination-averaged. From the LIST WG1 EMRI taskforce (2003).

M	m	e (final)	S/N(AET)						S/N(X)					
			(1wk)	(1mo)	(3mo)	(1yr)	(3yr)	(5yr)	(1wk)	(1mo)	(3mo)	(1yr)	(3yr)	(5yr)
$3 \cdot 10^5$	0.6	0.25	1.1	3.0	5.1	10.2	16.8	20.4	0.6	1.6	2.2	5.8	10.2	12.6
$3 \cdot 10^5$	10	0.25	27.8	60.3	80.4	119.0	149.0	162.0	16.6	38.0	48.8	74.7	95.4	104.0
$3 \cdot 10^5$	100	0.25	277.0	440.0	508.0	591.0	626.0	633.0	188.0	300.0	338.0	391.0	414.0	419.0
10^6	0.6	0.25	3.7	7.3	10.0	18.5	29.0	34.9	2.5	4.9	6.3	12.0	19.0	23.0
10^6	10	0.25	58.2	109.0	140.0	205.0	252.0	271.0	40.5	75.5	92.9	136.0	168.0	181.0
10^6	100	0.25	477.0	752.0	860.0	989.0	1060.0	1090.0	338.0	532.0	595.0	678.0	727.0	743.0
$3 \cdot 10^6$	0.6	0.25	3.1	6.0	8.0	14.1	21.2	24.9	2.2	4.2	5.4	9.5	14.3	16.7
$3 \cdot 10^6$	10	0.25	45.7	81.8	102.0	138.0	158.0	164.0	32.7	57.8	69.8	93.9	107.0	111.0
$3 \cdot 10^6$	100	0.25	344.0	508.0	559.0	590.0	601.0	604.0	244.0	360.0	391.0	411.0	418.0	420.0
$3 \cdot 10^5$	0.6	0.4	1.3	3.0	4.5	8.2	11.6	13.1	0.9	2.0	2.6	4.8	6.8	7.7
$3 \cdot 10^5$	10	0.4	24.9	46.7	56.7	69.2	75.3	76.6	16.1	29.1	33.8	41.3	45.1	45.9
10^6	0.6	0.4	3.4	6.7	9.2	16.6	25.3	30.0	2.3	4.5	5.8	10.7	16.4	19.5
10^6	10	0.4	52.8	96.9	122.0	177.0	223.0	241.0	36.4	66.3	80.3	116.0	147.0	159.0
10^6	100	0.4	405.0	639.0	743.0	871.0	926.0	938.0	284.0	445.0	504.0	586.0	623.0	631.0
$3 \cdot 10^6$	0.6	0.4	3.2	6.1	8.1	14.5	22.4	27.0	2.3	4.2	5.4	9.7	15.1	18.1
$3 \cdot 10^6$	10	0.4	46.3	84.5	108.0	162.0	208.0	226.0	32.7	59.6	73.2	109.0	140.0	152.0
$3 \cdot 10^6$	100	0.4	370.0	596.0	696.0	826.0	898.0	921.0	264.0	422.0	481.0	566.0	614.0	629.0

TABLE III: Baseline LISA, optimistic WD subtraction (5yr), volume-inc-averaged: $\overline{S/N} = (1/2 \int (S/N)^3 d \cos \iota)^{1/3}$. All values are for $\beta = 0$, $\lambda = 0$. Effect of position-in-the-sky averaging is $\pm 10\%$.

4.5.3 Make precision tests of dynamical strong-field gravity

When a binary black hole system coalesces a single, new black hole is formed. The formation of black holes in this way is the ultimate manifestation of strong and

dynamical gravity. With LISA we have the opportunity to test whether Einstein's theory correctly describes gravity in this most extreme regime. The gravitational radiation associated with the merger and its aftermath depends critically on the structure and composition of the binary components. The observation of the radiation from the inspiral will determine the initial masses and spins. The merger phase radiation will be compared with numerical simulations of the event using the field equations of general relativity. The mass and spin of the final merged black hole will be measured from the ringdown radiation it emits as it settles into a stationary state. This set of observations provides a unique link between the properties of stationary black holes, as measured by EMRI events (discussed above), with the dynamics of the strongest possible gravitational fields that lead to their production.

OR5.3: Observe the merger and ringdown radiation from all 1×10^5 to $1 \times 10^6 M_{\odot}$ black holes formed from approximately equal mass, $M_1 < 3M_2$, mergers to $z \leq 8$, measuring the mass and spin parameters, M and a , of the final black hole to $0.1M$. This will include essentially all systems with these masses as the rates are expected to be vanishingly small for higher redshifts (a $z < 5$ requirement, for example, would also include almost all likely events.).

Berti et al. (2005b) have studied LISA's ability to measure the mass and spin. Recent numerical relativity simulations suggest that merged black holes will have spins in the range $0.35 < a/M < 0.95$ (Campanelli et al. 2006), with 1% of the rest-energy radiated in the ringdown for equal-mass systems cite (Baker et al. 2006). For variations in the mass ratio, we generally expect the ringdown energy to scale with reduced mass squared. With these specifications, the results of Berti, et al indicate that the requirement is met with the standard sensitivity.

4.6 Probe new physics and cosmology with gravitational waves

One of the most surprising observations of recent years is the observation of the acceleration of the expansion of the Universe, whose origin is attributed to dark energy. This observation of acceleration of the expansion is based on the estimation of cosmological parameters through calibrated cosmological distances. LISA provides an entirely novel way to perform this calibration by detecting gravitational waves produced by the merger of massive black holes or by EMRIs. To estimate cosmological parameters, gravitational wave observations must be combined with a determination of the redshift of the merger. This would be obtained if an electromagnetic counterpart were detected.

Cosmological gravitational wave backgrounds are another domain of recent interest. Of all signals expected from LISA, they are probably the least likely, but any positive detection would be a major discovery. The scientific requirements are thus guided not by reaching a specific level of sensitivity but by ensuring that, if such a background is within the reach of nominal LISA, it is not missed.

The LISA sensitivity band probes the horizon scale of the primordial universe at a temperature corresponding to the TeV scale and above, when the horizon had a size of a millimeter or less. From the point of view of fundamental interactions, the TeV energy scale corresponds to the electroweak symmetry breaking scale – the Terascale frontier of known physics – whereas roughly 0.1 mm represents the frontier beyond which classical gravity remains to be probed. Thus LISA studies cosmology beyond the range of known physics. [For further discussion and references, see *LISA: Probing the Universe with Gravitational Waves* (LISA Mission Science Office 2007).]

On the observational side, the main constraint in the LISA frequency band at present is an upper limit coming from nucleosynthesis: $h_0^2 \Omega_{\text{GW}} < 3 \times 10^{-6}$. The rest is unexplored territory, covering several orders of magnitude; an optimistic value reached by LISA in a broad band is $h_0^2 \Omega_{\text{GW}} \sim 10^{-12}$.

4.6.1 Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured

Gravitational waves allow determination of the luminosity distance of a merger of two massive black holes. Combining this with a determination of the associated redshift provides a powerful probe of cosmogony. Possibilities include measurement of the Hubble constant (for mergers with $z \leq 1$) as well as a measurement of the cosmic acceleration rate (see e.g. Hughes 2002; Holz & Hughes 2005; Kocsis et al. 2006). Detection of prompt electromagnetic counterparts requires relatively rapid and precise localization of mergers to allow real-time and follow-up observations (Kocsis et al. 2007).

The observational requirements for this investigation are divided into three parts: pre-merger localization (OR6.1.1) and post-merger localization (OR6.1.2) of massive black hole mergers, and localization of EMRI events (OR6.1.3).

Pre-merger localization of MBH merger events. To facilitate searches for electromagnetic counterparts, the sky location of the event needs to be predicted in advance. A search area less than ~ 15 square degrees (comparable to the LSST field of view) is necessary, with 1 square degree fields or less being desirable. This leads to the following requirement.

OR6.1.1: LISA shall be capable of providing advance warning and localization of mergers of $0.5\text{--}3 \times 10^6 M_\odot$ black holes at $z=1$ with an accuracy of less than 15 square degrees one week before merger.

Calculations of the luminosity distance uncertainty and sky position uncertainty have been made by Kocsis et al (2007) for a variety of cases. These are an extension of the calculations reported in Kocsis et al. (2006). The calculations do not include the effects of spin precession which tends to improve parameter estimation for events with moderate or large SNR (see Lang & Hughes 2006). Their calculations thus represent a

conservative estimate of LISA capabilities and are computed for the case of median performance.

Figure 4-2: Advanced warning times (in days) for equal mass binary merger as a function of total mass M and redshift z for a variety of source parameters and LISA configurations. See captions and legends. From Kocsis et al. (2007).

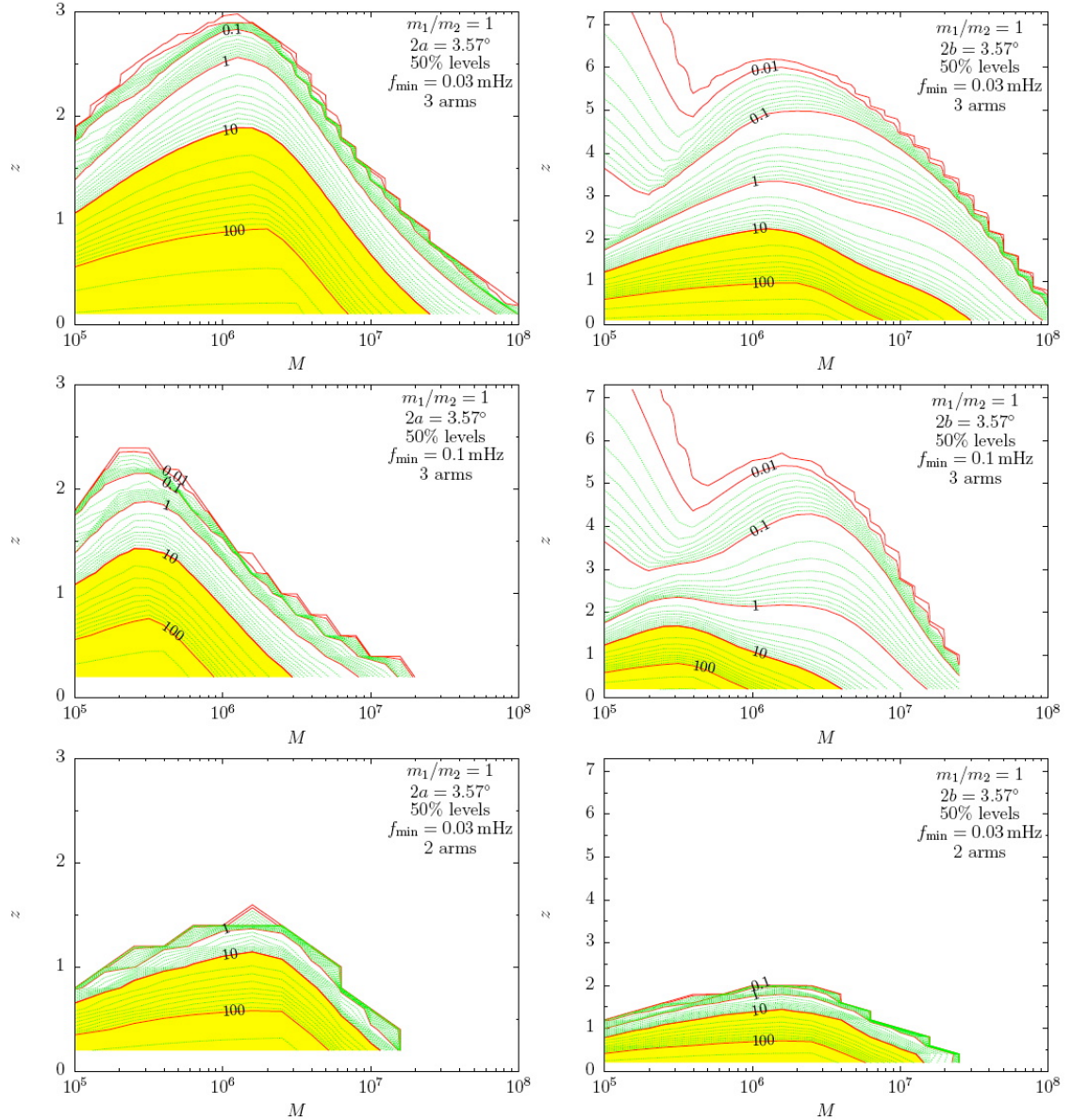


Figure 1: Advance warning times as a function of total mass M and redshift z when the major axis $2a$ (left) or minor axis $2b$ (right) first decreases under 3.57° (corresponding to LSST's field of view) using the full 3-arm LISA configuration (corresponding to two equivalent orthogonal-arm interferometers) with $f_{\min} = 0.03$ mHz (top), 3-arm LISA with $f_{\min} = 0.1$ mHz (middle). 2-arm LISA (neglecting one of the orthogonal-arm interferometers) with $f_{\min} = 0.03$ mHz (bottom). The ratio of component masses is $m_1/m_2 = 1$. The median (50%) distribution levels are shown for random binary and detector orientations.

Figure 4-3: Advanced warning times as a function of total mass M and redshift z for a variety of source parameters and LISA configurations. The mass ratio of the components is 10:1. See captions and legends. From Kocsis et al. (2007).

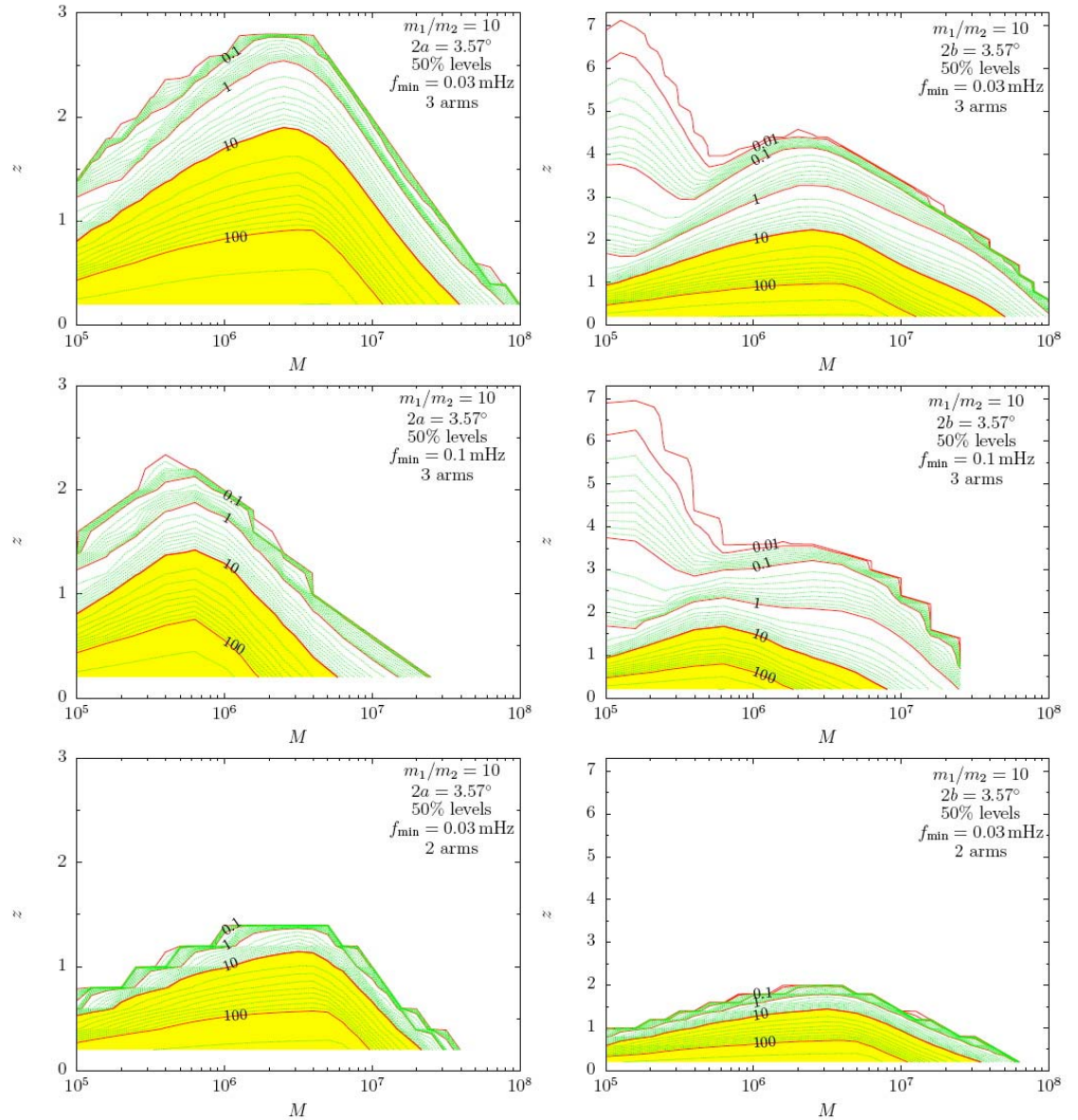


Figure 2: Same as Fig. 1, but for $m_1/m_2 = 10$.

A number of conclusions can be drawn from Figures 4-2 and 4-3:

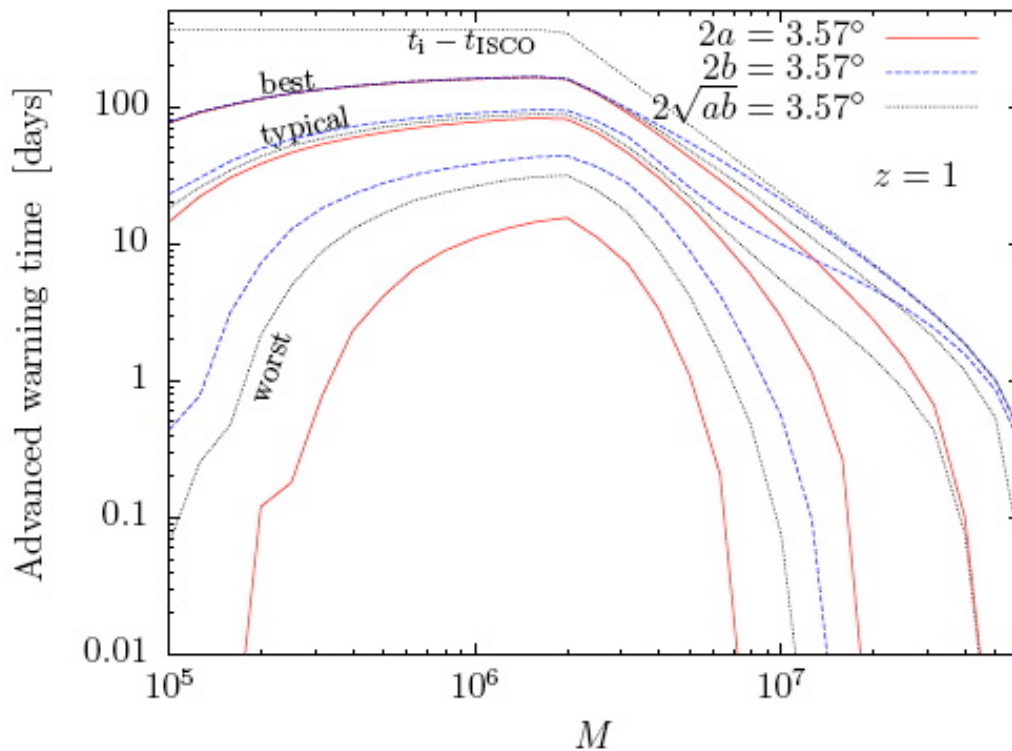
- For two arms (i.e. 1 interferometer or 1 IF) and a 0.03 mHz lower frequency cutoff the maximum redshift that can be observed with 10 day notice and 13 square degree localization is about $z = 1$ for total masses in

the range $0.5-3 \times 10^6 M_{\odot}$. Therefore the requirement for pre-merger localization is met with 1 interferometer. As can be seen, there is only a modest improvement in the range of redshift that can be reached for times shorter than 10 days before merger. This holds true for both equal mass and 10:1 mass ratios.

- For three arms (i.e. 2 IF) and 0.03 mHz lower frequency cutoff the maximum redshift that can be observed with 10 day notice and 13 square degree localization is about $z = 1.6$ for total masses in the range $0.5 - 3 \times 10^6 M_{\odot}$. The localization continues to improve up until merger with 13 square degree localization out to about $z=3$ for $10^6 M_{\odot}$. This holds true for both equal mass and 10:1 mass ratios.
- For a 0.1 mHz lower frequency cutoff, OR6.1.1 is not met for a 3-arm (2 IF) configuration and therefore would not be satisfied for a 2-arm configuration.

Figure 4-4 from Kocsis et al. (2007) shows the case of 2 IF and 0.03 mHz low-frequency limit and $z=1$ which show best, typical, and worst performance.

Figure 4-4: Advance warning time (in days) for equal mass binary inspirals at $z=1$, as a function of total mass, M (in solar units). Best, typical and worst cases refer to the cumulative error distributions for random orientation events. The advance warning times shown correspond to the values of look-back times when the major axis, $2a$ (red solid line), minor axis, $2b$ (blue dashed line), and equivalent diameter, $2\sqrt{ab}$ (grey dotted line), first reach an LSST-equivalent field-of-view (3.57°). Two interferometers are assumed. From Kocsis et al. (2007)



Post-merger localization of MBH merger events. Post-merger identification of a host galaxy requires extra precision in the luminosity distance to decrease the three-dimensional volume in which the host galaxy can be located. This leads to the following requirement.

OR6.1.2: LISA shall be capable of localizing the source direction to better than 1 square degree within one week after merger, and with uncertainties of less than 1% in the luminosity distance for black holes out to $z=2$ with component masses in the range $M = 10^{5-6} M_\odot$, when all three arms are operating.

Calculations of the luminosity distance uncertainty and sky position uncertainty have been made by Hughes (2007b) for configurations of LISA assuming both one and two interferometers (i.e., two arms with 4 operating links compared to three arms with six operating links). The calculations are shown in Table 4-6 and assume conservative low frequency performance of LISA. The table indicates that two interferometers are

needed to satisfy the requirement, and that LISA can fulfill the requirement for representative masses and mass ratios in the range $10^{5-6} M_{\odot}$ out to moderate redshift $z = 1-3$.

Table 4-6. Median values of fractional luminosity distance uncertainty and sky position uncertainty (major and minor axis) assuming the standard noise model, and randomly distributed position, orbital plane orientation, both spin orientations, and spin magnitude. These results provided courtesy of Scott Hughes (2007b).

M_1 (M_{\odot})	M_2 (M_{\odot})	z	D_L Uncertainty	Sky localization Uncertainty (major x minor)	D_L Uncertainty	Sky localization Uncertainty (major x minor)
			Single IF	Single IF	Two IF	Two IF
1.0E+06	3.0E+05	1	2.9%	(4.8x1.2) degrees	0.5%	(33x14) arcmin
1.0E+06	3.0E+05	3	20%	(38x6) degrees	0.7%	(40x18) arcmin

The time over which OR6.1.2 needs to be fulfilled is **TBD**.

Calculations by Lang and Hughes (2006) for two interferometers and a nominal LISA noise performance indicate that mergers with masses up to about $3 \times 10^6 M_{\odot}$ can be observed at $z=1$ with the luminosity distance and sky localization accuracy stated in the observational requirement. The calculations also show that mergers with the larger mass up to $1 \times 10^6 M_{\odot}$ and the smaller mass up to $3 \times 10^5 M_{\odot}$ can be observed at $z=3$ with sufficient accuracy to fulfill the requirement. Further calculations are required to establish the full range of masses and redshifts.

Localization of EMRI events. In addition to possible counterparts from massive black hole mergers, there may be mechanisms that could lead to EM counterparts for observed EMRI or IMRI events. From the GW signal, the luminosity distance to the source can be determined to of order $1/SNR$ (but somewhat worse than that, due to correlations with other parameters). For $SNR=50$ (the average SNR if the detection threshold is ~ 30), the distance can be determined to $\sim 3\%$ (Barack & Cutler 2004). Therefore even one such counterpart, allowing identification of the host galaxy and its redshift z , could give the Hubble constant H_0 to $\sim 3\%$. (Note that for $SNR=50$, the error box on the sky will typically be <5 sq degrees (Barack & Cutler 2004), which is within the realm of what could be reasonably surveyed.) The current systematic error on H_0 is of order 10%, so even one redshift identification would represent a large improvement over the current situation. And for N EMRIs detected with EM counterparts and redshifts, the error on H_0 becomes $\sim 0.03/\sqrt{N}$.

The following requirement is driven by the capability to use EMRI observations to determine the Hubble constant H_0 to $<3\%$.

OR6.1.3: LISA shall have the capability to measure distance to EMRI or IMRI sources with $\text{SNR} > 50$ to 3% or better with a sky position better than 5 square degrees.

4.6.2 Measure the spectrum of, or set bounds on, cosmological backgrounds

The LISA band is ideally placed for detecting gravitational waves produced by bubble collision and turbulence during a first order phase transition at the Terascale. By 2014, we should have identified the nature of the electroweak phase transition at the Large Hadron Collider and thus know what to expect for LISA at TeV scales. In addition LISA has sensitivity to transitions at somewhat higher energies than 1 TeV.

In the context of the theory of strings and branes, the possibility has appeared that some extra dimensions have a dimension in the submillimeter range. Gravitational waves can be used as a probe of these extra dimensions. In this context, the TeV scale may play a special role for which LISA is ideally suited. There are then several scenarios leading to gravitational wave production, again describable as phase transitions.

This investigation will search for a stochastic background of gravitational waves produced during a first order phase transition in the early Universe or a primordial stochastic background produced by quantum processes shortly after the Big Bang (OR6.2.1) as well as search for the signature of a population of cosmic strings (OR6.2.2).

OR6.2.1: LISA shall be capable of detecting or setting an upper limit on the spectrum of a stochastic background of gravitational waves produced during first order phase transitions in the 100 GeV to 10^3 TeV energy range, limited by the instrument sensitivity model.

In order to confirm the existence of, or set limits on, isotropic stochastic backgrounds, it is necessary to ascertain the instrumental and environmental noise and differentiate it from gravitational wave noise with moderate frequency resolution over a broad band. The symmetric Sagnac signal combination is an elegant technique for measuring this noise since it provides a way to modulate the gravitational wave sensitivity without making any physical changes in the system. It requires however that six links operate for some period of time, so an independent backup technique is desirable.

Cosmic strings are predicted in some modern theories of fundamental interactions, whether they appear from the breaking of abelian symmetries or as macroscopic structures in the context of fundamental string theories. They are one-dimensional defects in the physical vacuum, stretched to enormous length by the cosmic expansion. The key parameter is the string mass per unit length in units of Planck mass $G\mu$; current limits suggest that this is so small that the only observable effect of cosmic

strings will be the gravitational radiation from oscillating loops. The corresponding spectrum of background gravitational waves is expected to be rather flat over many decades in frequency. LISA will probe several orders of magnitude below the current limit from millisecond pulsar timing.

OR6.2.2: LISA shall be capable of identifying the signature of cosmic strings by detecting or setting an upper limit on the spectrum of the stochastic background from a population of decaying string loops, limited by the instrument sensitivity model.

The ultimate goal in cosmology is to observe the cosmological gravitational background produced in the first instants of the Universe, that is, during the inflation epoch. In the simplest (slow-roll) inflation scenarios, the spectrum is rather flat but it is expected to lie well below the LISA sensitivity: $h_0^2 \Omega_{GW} < 10^{-15}$. In more elaborate models (especially in the context of string theory), it may be within reach of LISA. It should be stressed that such scenarios are still to be developed into full-blown cosmological models. No observational requirement is therefore stated for detection of gravitational waves from the epoch of inflation.

4.6.3 Search for burst events from cosmic string cusps

Gravitational wave bursts are occasionally expected from cusps of oscillating cosmic string loops beamed in our direction. Although individual bursts give a clear signature from their universal waveform, the first detection of a string loop population will probably be their integrated stochastic confusion background (see above). The other source of gravitational wave bursts is the relativistic collapse of very massive objects. An upper limit of one per day is already constraining models.

OR6.3: LISA shall be capable of detecting or setting an upper limit on the rate of cosmic gravitational wave bursts, limited by the instrument sensitivity model.

4.7 Search for unforeseen sources of gravitational waves

In addition to exotic sources with predictable signals, such as first-order phase transitions, inflaton decay, warped extra dimensions, and cosmic strings, there may be other phenomena in the Universe that can create considerable gravitational wave activity but for which there is no evidence from electromagnetic radiation or particles. There may be new purely gravitational structures, such as entirely new kinds of black holes that nobody has thought of. There may also be new dark or "hidden" sectors of mass and energy that do not communicate with the Standard Model particles except through gravitational interactions; certainly many ideas of this kind have been put forward with regard to explanations of cosmic Dark Matter and Dark Energy. Indeed those two puzzles are examples of new physics already discovered only via gravity, and there may be surprises of a similar magnitude in store once we explore the universe deeply with gravitational waves. LISA will provide a sensitive exploration tool of unprecedented sensitivity in this domain.

This science investigation associated with this science objective requires that after the data stream is fit for all known classes of astrophysical sources, instrumental and environmental artifacts, models will be developed and tested for what remains. This will include both apparently structured, non-gaussian signals, and also new quasi-gaussian backgrounds with spectra that do not agree with the predictions of calculated sources in 4.6.

OR7.1: LISA shall be capable of a discovery space for unforeseen effects (i.e. even at frequencies where we cannot predict likely signals from known classes of astrophysical sources.), limited by the instrument sensitivity model. LISA shall allow for reliable separation of real strain signals from instrumental and environmental artifacts, when all three arms are operating.

5 MINIMUM REQUIREMENTS

The minimum science requirements are based on:

- 1) Preserving the probability that a reasonable number of massive black hole binary merger events will be detected; and
- 2) Maintaining sufficient sensitivity to make sure that the expected instrumental sensitivity can be verified by observations of both known and unknown galactic binaries.

This ensures that all but one high-level science objectives are addressed, although in some cases with degradation or elimination of capability to carry out some of the specific investigations relevant to the science objective.

In particular:

- The primary science enabled by detection and characterization of massive black hole mergers is maintained, but with degraded performance and shorter mission duration (Science Objectives 4.1, 4.2, 4.5)
- A reduced capability for detecting Galactic compact binaries is maintained allowing a subset of the corresponding science objectives to be addressed (Science objectives 4.3, 4.4 and 4.5)
- A reduced capability is maintained in certain frequency ranges for detecting cosmological backgrounds, bursts, and other new phenomena (Science objectives 4.6 and 4.7)
- Depending on event rate, there will be a severe degradation or elimination of capability to address the science enabled by observations of EMRI events (Science objectives 4.3 and 4.5)

5.1.1 Observational Requirements

ORmin1) LISA shall have the capability to detect MBH mergers with $M_1=1-3 \times 10^6 M_\odot$ and mass ratio $M_2/M_1 = 0.1$ at $z=2-6$

ORmin2) Lisa shall have the capability to detect and study 3 or more optically observable verification binaries between 1 and 10 mHz with $SNR > 20$ in 2 years of mission lifetime.

This will verify that LISA is operating correctly thus providing confidence in all other results. Sensitivity levels required for detection of the verification binaries will also allow detection of ~1000 other white dwarf binaries including the interesting tidal-dissipation sources and SNIa/AIC progenitors of the optically observable binaries.

5.1.2 Minimum Requirements

The minimum requirements are satisfied by an instrument strain sensitivity that is at a level five times higher than the baseline instrument sensitivity model and that extends from 0.1 to 10 mHz.

In addition to the strain sensitivity requirements, there are three additional minimum requirements:

MinR1) Science mission duration of 2 years

MinR2) Capability to provide continuous data availability during 4 day period prior to and including final merger, specified two weeks before the event. No scheduled system down time during this period.

MinR3) A duty cycle (η) greater than 0.75

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APPENDIX A – ACRONYMS

BH	Black hole
CWDB	Compact white dwarf binary
EM	Electromagnetic
EMRI	Extreme mass ratio inspiral
ESA	European Space Agency
Gpc	Gigaparsec
GRS	Gravitational Reference Sensor
GW	Gravitational wave
IMBH	Black hole, with $10^2 M_{\odot} < M < 10^4 M_{\odot}$
IMRI	Intermediate mass ratio inspiral
ISM	Instrument Sensitivity Model, defined in Chapter 3
LISA	Laser Interferometer Space Antenna
LMC	Large Magellanic Cloud
MBH	Massive black hole, with $10^4 M_{\odot} < M < 10^7 M_{\odot}$
mHz	millihertz
MRD	Mission Requirements Document
NASA	National Aeronautics and Space Administration
OR	Observation requirement
ScRD	Science Requirements Document (to distinguish from SRD, used by ESA to refer to the Systems Requirements Document)
SMC	Small Magellanic Cloud
SNR	Signal-to-Noise Ratio
TBD	To be determined
TBR	To be reviewed
TDI	Time Delay Interferometry

APPENDIX B – GLOSSARY

Compact white dwarf binary (CWDB) – A pair of mutually orbiting white dwarf stars which are very close together.

Extreme mass-ratio inspiral (EMRI) – A situation where a compact object is spiraling into a massive black hole in a galactic nucleus, and where the mass ratio m_2/m_1 is very small: less than 0.01. In cases where the compact object is a white dwarf, neutron star, or stellar-mass black hole (BH), the ratio of mass $m_2/m_1 \sim 10^{-6} - 10^{-5}$.

Intermediate-mass black hole (IMBH) - A black hole with mass M in the range $10^2 M_\odot < M < 10^4 M_\odot$.

Intermediate mass-ratio inspiral (IMRI) – A situation where an intermediate-mass black hole is spiraling into a massive black hole in a galactic nucleus, and where the mass ratio is $m_2/m_1 \sim 10^{-3} - 10^{-2}$.

M_\odot – Solar mass, 2×10^{30} kg.

Massive black hole - A black hole with mass M in the range $10^2 M_\odot < M < 10^4 M_\odot$.